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ORIGINAL ARTICLES.

The Centenary of Lyell's "Principles of Geology".

By Philip Lake, M.A., F.G.S.

IN the literature of geology there is no book that has exercised a more lasting influence on the science than Lyell's *Principles of Geology*, the first volume of which was published a hundred years ago. The twelfth and last edition appeared in 1875, some months after the author's death. The active life of the work thus extended over some fifty or sixty years, while indirectly its influence still survives.

Yet the *Principles of Geology* was not a work of profound originality nor was Lyell a great field geologist in the same sense as Sedgwick or Murchison. His chief merits were the sanity of his judgment and his freedom from prejudice, his determination to examine evidence for himself so far as that was possible, and his clearness of thought and expression. It is true that Fitton,[1] in 1839, reviewing Lyell's *Elements of Geology* but referring to the *Principles*, says of their author, " Speculation is his great delight, and is too often indulged in. He takes up a new conjecture with evident enjoyment. . . ." But most geologists will be more inclined to agree with the writer of a notice in *The Times Literary Supplement* last March that " Lyell's mind was unadventurous, cautious, and orderly ". Perhaps unadventurous is not quite the right word, for in 1830 Lyell was tilting at the collective wisdom of the Geological Society, where cataclysmal views were dominant, though not universal, amongst his fellow-members. Even the sceptical Greenough, who criticized the opinions of everyone else and did not believe in his own, was convinced that there had been a world-wide deluge. Before many years had passed, however, the uniformitarian views of Lyell prevailed.

To understand the great influence of Lyell upon the thought of his generation we must bear in mind the conditions of the period. Geologists were not then a class set apart from the rest of mankind by a long and laborious course of study. They were for the most part educated men with no special training. It was to educated men in general that Lyell's book was addressed, and the number of new geologists that he created must have far exceeded the number of old ones that he converted. It is different now. The educated man of to-day knows nothing of anabohitsite or *Parapoponoceras*, and he cannot even read *The Face of the Earth* with any real pleasure. The article by Fitton to which reference has already been made occupies sixty-one pages of the *Edinburgh Review*. Imagination recoils at the fantasy of a modern *Review* allotting sixty pages to a notice of a new geological work.

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[1] *Edinburgh Review*, vol. lxix, p. 410. That this unsigned review was by Fitton is shown by Mr. T. Sheppard in the Geological Magazine for 1924, p. 192.

Fitton protests that Lyell does not do justice to his predecessor Hutton. Many geologists think that Hutton was the founder of modern geology, but few have read his *Theory of the Earth*. Perhaps he was a founder, for he was greater than his book; but his theory was not a foundation stone and most of it has crumbled away.

Briefly stated Hutton's theory is this. The rocks that form the land are broken up by weathering agents, and the loose material is washed into the sea by running water. It does not remain near the shore, but is carried into the "unfathomable depths" of the ocean. It is there consolidated by fusion due to the heat of the earth's interior, the pressure at that great depth preventing the loss of carbon dioxide and of other volatile matters. The consolidated strata are at times lifted above the sea to form new land, and the process begins again. He does not know exactly how the elevation is accomplished, but supposes that it is caused in some way by the internal heat. He holds that nine-tenths or ninety-nine hundredths of the rocks that we see have been formed from pre-existing rocks in the manner described.

The greatest surprise to a modern reader is to find that the consolidation of sedimentary rocks, including even coal, is attributed to fusion. The author spends more than a hundred pages in proving that no other cause will explain it, and that fusion will; and he leaves no room for doubt that he uses the word in its ordinary sense.

Much of the prolixity of Hutton's book is due to his wearisome reiteration of the excellent maxim that we must not imagine causes but must reason only from what we know to happen; but he does not always practise what he so tediously preaches. He ridicules those who reason from what they see in caves and petrifying springs, and think that consolidation may be due to infiltration; while from a careful examination of a septarian nodule he himself concludes that nothing but fusion can have produced it. It seems strange to us that both Hutton and Playfair regarded the septarian nodule as a conclusive proof of the fusion theory. Doubtless there are similar conclusive proofs of theories to-day, and it may be instructive to consider how two such men could be led so far astray. Hutton assumed as a self-evident truth that the loose material brought down from the land could find no permanent resting-place till it reached the depths of the ocean, and that consolidation took place there. It was this prepossession that led him to reject every hypothesis but that of fusion.

Very little of Hutton's theory is left in modern geology and none in the modernist type. His philosophy, upon which he thought his theory was based, is another matter, although it is almost universally confounded with the theory. He believed that the causes which we see in action to-day are the same that have always acted since the beginning of geological history, and that, with time enough, they are sufficient to account for the phenomena of the past. Rather illogically he argues that therefore there has been time enough and there have been no other causes.

Lyell gives full credit to Hutton for his philosophy and passes so lightly over his errors that the reader is scarcely aware of them. There is no ground for Fitton's strictures; but Fitton, during his student days in Edinburgh, probably came under Huttonian influences. He was one of the few supporters of the Huttonian theory at the Geological Society and was perhaps especially jealous for the honour of its founder. He even suggests that Lyell was indebted to Hutton for all his main ideas and did little more than fill in the outline drawn by Hutton. It is not the resemblance between the views of Hutton and Lyell that strikes the modern reader, but rather the difference in their outlook. Hutton went far beyond his evidence, with fantastic results; Lyell, with much more evidence at his disposal, was more cautious, and there is nothing fantastic about the *Principles* even when he is wrong. The difference in outlook is reflected in the titles of their books. Hutton frames a theory which he believes to be complete in all essentials. Lyell has no theory, but seeks to establish principles upon which investigation may safely proceed. One of his principles is that which Hutton also professed; but Hutton thought he knew the causes which are in action to-day, and Lyell tried to find out what they are.

It is evident that between the days of Hutton and those of Lyell geology had become a science, and it was during this period that its foundations were firmly laid. But they do not rest upon the theory of anyone, and we know that Hutton's platitudes had no great effect beyond a limited circle. William Smith relied upon his own commonsense. So did many who made useful contributions to the science and yet believed in a universal deluge. It is interesting to read Greenough and to realize how strong was the case for a great débâcle until the glacial deposits of Northern Europe had been recognized as glacial. But the controversies of the period have obscured the history of the science, and the story of the steps by which real progress was made remains to be written. Hutton's chief contributions to that progress were neither his theory nor his philosophy, but his proof of the intrusive nature of granite and his demonstration of an unconformity with his explanation of its significance.

Lyell was a uniformitarian in the strictest sense of the word. But his uniformitarianism was not a theory ; it was an attitude of mind. He did not deny, for example, that geological agents may have acted more intensely in the past ; but he would not believe it without proof. It is a reasonable attitude, but not the only reasonable one. It is not foolish to recognize the limitations of our knowledge and experience, to believe that there are causes of which we are still ignorant, or to think that there may have been greater geological events than have occurred during the short period of our observations. Each attitude of mind has its own dangers, and the chief danger of the uniformitarian attitude is that the mind may be closed to new ideas. But Lyell's natural open-mindedness and freedom from prejudice saved him from this. In the early editions of the *Principles* he pronounced definitely against the transmutation of species. He was, however, convinced by the arguments of Darwin and became one of the firmest supporters of his views. It is well known that Darwin was more encouraged by the conversion of Lyell than by the great success of his book. Lyell was no specialist, and the high value that Darwin attached to his judgment is a clear indication of the qualities to which Lyell's influence was chiefly due.

To follow the later history of the *Principles* would lead us too far. The uniformitarian doctrine soon supplanted all others, in Britain at least, and remained dominant till long after Lyell's death. Probably it protected us from many extravagances, but those who professed it did not always show Lyell's judgment. In the hands of authority it sometimes became " The causes that *we* know are sufficient to account for the phenomena of the past, and there are no others " ; and the working geologist was debarred from expressing the modest ideas that sprang directly from his work, because they were " theoretical ". There is little need now, however, to dwell on the dangers of the uniformitarian attitude. There is nothing uniformitarian about post-war geological theories, and there are so many of them that it is difficult not to keep an open mind. Meanwhile geology progresses in spite of theories.

The Petrography of the Hunstanton Red Rock.

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ALTHOUGH the conspicuous band of red rock seen in the cliff at Hunstanton is well known, and the literature of the subject is voluminous, current ideas as to its true nature and origin are somewhat vague and unsatisfactory. None of the previous workers who have examined it have come to any very definite conclusion, and modern methods of sedimentary petrography do not seem to have been applied to it in much detail, although it is briefly described by Messrs. Versey and Carter in their valuable study of the Carstone of Yorkshire and Lincolnshire.[1] There are, however, a considerable number of published chemical analyses of bulk-samples. In the following pages an attempt is made to describe in more detail than heretofore the petrographical and mineralogical characters of this remarkable deposit.

At the outset a difficulty arises in selecting a working name for it. At an early date Professor Judd somewhat unfortunately used the name " Hunstanton Limestone " to include all the red Cretaceous deposits of Lincolnshire and Yorkshire, which are not dealt with here. The term " Red Chalk " is undesirable, owing to its stratigraphical and palaeontological implications, which are also carefully avoided. Therefore the entirely non-committal name of " Hunstanton Red Rock " is here adopted, on the understanding that it includes only the exposures in N.W. Norfolk.

Before proceeding with the detailed descriptive portion of this paper it may be well to clear up a curious misunderstanding which has crept into the literature. Writing in 1876 Barrois quoted with approval (in English) a sentence from an earlier paper by Judd, as follows : " The Hunstanton limestone, which is conformable with the upper Cretaceous beds, but unconformable with the Neocomian . . ." This sentence is again quoted by Kitchin and Pringle, in support of their main argument.[2] Now a very brief examination of the cliff at Hunstanton suffices to show that this statement is there physically inapplicable, as the field relations exhibited are exactly the contrary.

The explanation of this contradiction appears to be as follows : the paper by Judd from which the quotation comes deals chiefly with the Red Chalk of Lincolnshire and Yorkshire, which he designates throughout by the name of the " Hunstanton Limestone ", and the " Conclusions ", from which the sentence is quoted by Barrois, refer only to those counties. Twenty pages earlier in the same paper in an incidental description of Hunstanton Cliff Prof. Judd writes as follows : " The bed of red limestone is at this place 4 feet in thickness and is divided by very distinct planes of stratification into three nearly equal courses. The lowest of these courses graduates into the Carstone beneath, while the upper one is separated by a variable seam of red clay from the ' Sponge Bed ', a layer of hard white chalk 15 to 18 inches thick and full of the so-called ' *Spongia paradoxica* ' ; there is never any appearance of gradation in colour between the red and the white beds."

This a perfectly accurate description of the cliff section. Two years later Prof. Wiltshire also wrote : " Towards the base of the bottom bed (c) the hard limestone character of the Red Rock is lost and the stratum degenerates into a somewhat sandy incoherent mass hardly differing from the underlying division [the Carstone] except in colour . . . " Also " Resting on the top of A [the top bed of the Red Rock] and filling the undulations on the underside of the lowest white bed (b) is a bright red argillaceous substance, very friable, without sand and apparently destitute of organic remains, and never exceeding two or three inches in thickness."

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[1] Versey and Carter, *Proc. Yorks. Geol. Soc.*, vol. xx, 1926, p. 349.

[2] Kitchin and Pringle, 1922. See bibliography at end of this paper.

From these quotations it is clear that these writers recognized the fact that at Hunstanton there is no physical break between the Carstone and the bottom of the Red Rock, and that the top of the Red Rock is separated from the base of the white Chalk by a physical discontinuity. Moreover in 1886 Mr. W. Whitaker, in the discussion on Sir A. Strahan's paper on the Carstone in Lincolnshire said " he agreed as to the conformity at Hunstanton between the Red Chalk and the Carstone " (Q.J.G.S., vol. xlii, 1886, p. 493).

I have considered it necessary to labour this point somewhat in vindication of the accuracy of these early field observers. It so happens that I deliberately refrained from reading the literature of the subject before visiting the locality and collecting material for the purposes of the present paper: therefore a copy of my own field notes of the section, about 30 yards from the point where the whole series disappears towards the north and whence one set of the material now to be described was collected, is here appended.

		ft.	*in.*
	Normal white chalk		
	Sponge bed	1	2
	Lower surface irregular with layer of soft iron oxide		0–2
3 ft. 11 in.	Nodular pale pink bed		5
	Nodular pale pink bed		9
	Red band		3
	Nodular band	1	0
	Uniform band	1	6
	Coarse brown sand	+6	0

In the year 1909 I wrote as follows concerning the relation of the Red Rock to the strata above and below[1]: " It rests regularly and evenly on the Carstone and there is no sign of erosion or unconformity between them. The thickness is about 4 feet, and three slightly different bands can be recognized. The lowest part is softer and more calcareous and contains a good many quartz grains like those in the sandstone below. The central part is a dark red rough nodular limestone with many fossils, while the highest band, about 1 foot thick, is a hard light red or pink limestone, mottled with white and more calcareous than the rest. There is at the top a seam of ferruginous earth separating it from the Chalk."

As will appear from the field notes already quoted I see no reason whatever to depart from this earlier description, which was written without any ulterior object in view. It is obviously entirely inconsistent with the contention of Messrs. Kitchin and Pringle, that the Red Rock is unconformable to the Carstone, but continuous with the Chalk, and agrees completely with the older descriptions of Judd and Wiltshire, already referred to. Moreover it is completely borne out by the present petrographical investigation.

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[1] *Geology in the Field*, Jubilee Volume, Geol. Assoc., 1909, p. 152.

This discussion raises the question of the meaning of *conformable* and *unconformable*. If on palaeontological grounds a conformable series is to be interpreted as covering a set of strata with an obvious physical break in the middle, while an unconformable series can show a perfect lithological transition with no visible physical break all, it is clear that these terms are in need of re-definition.

THE HUNSTANTON CLIFF SECTION.

Although the Red Rock is visible for a distance of about a mile in the cliff at Hunstanton, it is only accessible at the north end of the section, where the dip brings it down to beach-level, to disappear finally under a mass of sand which forms the coast-line beyond. Since in this work the exact horizon of all specimens is important, attention was confined to the accessible rock in place, and all loose material was ignored. As the whole visible length of rock is remarkably uniform in character there can be no doubt that this section is quite representative: in all essentials the section at Snettisham is similar, except that it is incomplete at the top. The gradualness of the transition at the bottom is perhaps even more marked at Snettisham.

THE RED ROCK AT SNETTISHAM.

Just to the north of the village of Snettisham there are three large quarries in the Carstone; the most northerly, which is close to the main road, was in active operation at the time of my visit (July, 1929). However it is mainly in the massive well-jointed and hard part of the Carstone, and shows nothing of particular interest. At the top it just shows the soft bed to be mentioned presently. The other two are approached by a rough sandy lane leaving the main road just at the first-named quarry. The first of these, now abandoned, is of the same character as that just described, but smaller, and needs no description. The third, however, the one nearest to the village down this same lane, is of great interest. It does not seem to be referred to in most of the older literature, and my attention was first drawn to its existence while reviewing a book mainly concerned with architecture, *The Old Cottages and Farm Houses of Norfolk*, by C. J. W. Messent (Norwich, H. W. Hunt, 1928). This author takes an unusual and praiseworthy interest in the geology of his materials, and gives a very good description of this section. He says: " The chief pit shows the following section: below 2 feet of surface soil 2 feet of white Chalk is found, then 3 feet of red chalk; directly beneath this comes the Carstone, which is loose for about 5 feet and solid for at least another 15 feet."

The 2 feet of white Chalk, however, is not solid undisturbed rock, but a kind of brashy breccia, and the upper surface of the Red Rock is very irregular and nodular; in fact a solution surface due to recent weathering. The rest of the description is perfectly accurate. The highest 5 or 6 feet of the Carstone are not much consolidated and unjointed, whereas the lower bed is much harder and well-jointed, vertically as well as horizontally. There is a marked line of change at the top of the last-named, and its base is not seen. It cannot, however, be very thick in this area, as the boggy type of soil due to the Snettisham Clay soon comes on conspicuously west of the main road a little further north, at a level which cannot be much lower than the floor of this pit, and this clay is also mapped in the village by the Geological Survey, Sheet 69.

METHODS OF INVESTIGATION.

The primary object of the present investigation was to determine whether, and to what extent, petrographical methods could throw light on a problem in which palaeontology had led to confusing and conflicting results. Therefore the first principle obviously was to ignore fossils altogether and to rely solely on the mineralogical constitution of the strata. For this purpose during the summer of 1929 sets of specimens were collected from the available outcrops. The two sections relied upon for this purpose were the northern end of the Hunstanton Cliff, where the Red Rock descends to beach level and becomes accessible, and the old quarry at Snettisham where the same rock is well exposed as just described. The distance between these two localities is about 5 miles. It is quite certain that between Hunstanton Cliff and Snettisham there is no exposure, although in a Chalk pit just south of Heacham the Red Rock must be very near the surface, and undoubtedly outcrops in a ploughed field adjoining this pit on the south: the red colour of the soil in this field is noticeable.

From the exposure at the north end of the Hunstanton Cliff a series of specimens were taken at frequent intervals from the top of the Carstone up to and including the lowest bed of the Chalk, the so-called Sponge-bed. As the total thickness of the Red Rock is here about 4 feet, and ten specimens were taken from it, all of which were about 4 inches in depth, it is obvious that this collection represents a nearly continuous section of the rock; from the Carstone to the Chalk. In this series the only visible physical break is between the top of the Red Rock and the base of the Sponge Bed. The passage from the Carstone to the Red Rock is manifestly continuous, as noted by Judd and Wiltshire. Another precisely similar series was collected at Snettisham; here, however, as explained above, the succession is incomplete at the top and the Chalk is not truly in situ.

A good deal of preliminary work was done on specimens not included in these series, in order to ascertain the best methods, before the systematic examination of the series was begun. As a result of this preliminary work the following method was adopted : the rock, which is usually very hard, was crushed in a mortar and passed through a 30-mesh sieve. The fine material was treated with cold 10 per cent commercial hydrochloric acid until all effervescence ceased. The insoluble residue was washed till free from red mud, and dried for further examination. From certain specimens also the red mud was collected and dried, a wearisome operation owing to its excedingly fine state of division. Experiments showed that the process of sieving did not make much difference, if any, in the final composition of the residue, but in critical cases, especially in the uppermost layer of the Red Rock, large lumps were dissolved in acid without crushing or sieving. The grains which would not then pass through the sieve were precisely similar to the largest grains which did pass through, being mainly quartz or some cherty-looking substance.[1] The Chalk (Sponge-bed) was not crushed at all, but treated in large lumps, in order to avoid loss of any constituents, and also so that the etching effect of the acid on this and on the Red Rock treated in the same way could be studied. There proved to be characteristic differences between them in this respect. Furthermore a few specimens of typical Carstone from well down in the series, as well as several from just below the Red Rock, received precisely similar acid treatment for comparison.

It is unnecessary to give a general account of the ordinary petrographical methods employed in the further examination of the residues : some special points will be mentioned later.

GENERAL RESULTS.

The first conspicuous result of the particular treatment adopted was that the Red Rock is clearly divided into three fractions :

(1) the calcareous material, which is completely dissolved.
(2) the red colouring matter, which can be removed by decantation.
(3) a brown sand.

As to the dissolved calcareous material, nothing more need be said. The red colouring matter obviously varies in amount in different specimens, on the whole decreasing from below upwards, as is indeed clear from the general appearance of the rock in the field. I should say it would be practically impossible to collect and weigh it, as it sticks persistently to dishes, beakers, filter papers, or anything else with which it comes in contact, and is most difficult to dry ; in fact nothing short of ignition at a high temperature could give anything like constant water-content. Its behaviour is very like that of the ordinary ferric hydrate precipitated from a soluble iron salt by ammonia. This point is of importance as throwing light on its nature : this will be discussed again later.

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[1] Some of these larger bodies may be phosphatic, although chemical tests for phosphate in the finer material gave negative results.

Still more interesting is the nature of the third fraction, the brown sand. To cut the matter short, this is just simply Carstone. The samples prepared from the Red Rock by this method are indistinguishable from specimens of the Carstone below which have undergone similar treatment. A most important point is that the brown hydrated iron oxide so characteristic of both is not attacked by cold acid of the strength here used. In order to remove this brown oxide from either it is necessary to boil with concentrated HCl, or even, to get a perfectly clean sample, with aqua regia. It is necessary to resort to this rather drastic method to obtain material suited for heavy mineral determinations, and the results, which are somewhat surprising, will be described later.

It will be well to state also at this point that the products of the treatment of samples of the "Sponge-bed" by the same method showed no resemblance whatever to those obtained from even the highest part of the Red Rock. A discussion of this point will also be found in a later section.

Before discussing in detail the nature of the Red Rock and of its constituents, it is necessary to give a somewhat full description of the petrography of the Carstone, because a comparison between the two formations constitutes a very important part of this paper. For this purpose the specimens collected from the third quarry at Snettisham, nearest to the village, are selected as typical, as this section is less well known than the Hunstanton Cliff and in some ways more interesting.

As before stated this quarry shows, below the Red Rock, which is here only about 3 feet thick, 5 or 6 feet of rather loose brown sand without conspicuous jointing, resting on a considerable thickness of a much harder and well-jointed Carstone, such as is used for building. The transition from the upper sand to the Red Rock is is quite gradual, with no definite line of division, although as seen from a distance the change of colour is well marked.

The lower well jointed rock is macroscopically a coarse gritty sandstone, fairly even in grain. When crushed and washed and then treated with dilute HCl, there is quite brisk effervescence and much yellow-brown mud is released, showing that even many feet below the Red Rock the Carstone is quite calcareous. A specimen of Carstone from 1 foot below the Red Rock at Hunstanton Cliff (100 grams) yielded 79·3 grams of sand, when treated with dilute acid and washed in the standard way adopted for the Red Rock.

A sample from the uppermost foot of the soft Carstone is softer and redder than the last and very calcareous, so that it needed a lot of acid treatment : otherwise this specimen is very like the last.

A third specimen from the top 3 inches of the Carstone is still softer and redder, and the fine mud removed by washing is distinctly red, instead of yellow-brown as in the other two.

However, in all these cases the final residue of sand, after mud and calcareous matter had been removed by washing and dilute HCl, is precisely similar, and one general description will suffice for these and specimens from the other quarries at Snettisham and from Hunstanton: the variations are only in the texture of the rock, its colour *before* treatment and in the material removed by such treatment. These variations are of importance in the subsequent discussion.

The following description may be taken to apply to specimens from all localities, the main difference being that at Hunstanton the rock is much less calcareous, sometimes showing no effervescence at all.

THE PETROGRAPHY OF THE CARSTONE.

When washed and cleaned in the standard way all the specimens of Carstone are essentially similar, so that one general description will suffice. There are, of course, variations in size of grain, but the larger fragments which do not pass a 30-mesh sieve appear to be precisely similar to the smaller quartz grains and rock-fragments which do pass such a sieve. Furthermore, samples from Hunstanton Cliff are quite indistinguishable from similarly treated samples from Snettisham, 5 miles away. Some specimens are entirely free from calcium carbonate, while a few effervesce freely with acid.

The general colour of the washed sand is a bright yellow-brown; in fact the characteristic colour of hydrated ferric oxide. It has also a characteristic speckled appearance owing to the presence of a considerable proportion of very dark grains to be described presently. Very few grains are colourless, and the great majority of even the quartz grains have a distinct yellow tinge. This is purely a superficial iron stain, and can be removed by strong acid, leaving the quartz perfectly colourless. The majority of the dark grains just referred to are spherical or spheroidal, with sometimes a slight depression in the middle of the flatter surface. They are either brown or black in colour, very smooth and usually with a high polish. These grains are the most characteristic feature of the sand, and it is to be noted that they strongly resemble the ferruginous ooliths of certain Lower Cretaceous ironstones, e.g. Claxby and Donington, Lincs., of which specimens were prepared for comparison.

In order to ascertain the true nature of these grains, a number of the roundest, blackest, and mostly highly polished were carefully hand-picked from each of several samples. These were boiled with strong acid (actually aqua regia) till all colour had disappeared. Some proved to have a core of green glauconite, while others left as a residue colourless, or pale pinkish spheres, which very readily absorbed an aniline dye, and were presumably some form of silica, as in the ooliths of, e.g. the Cleveland ironstone. It thus appears that these grains are of a concretionary, oolithic nature, and that they can be formed round nuclei of different kinds. In one or two cases it was suspected that the nucleus was a grain of quartz, but this was not proved beyond doubt. In all washed specimens a few grains of green glauconite without any coating can also be seen, and on acid treatment this substance becomes very conspicuous.

For further petrographical investigation fairly large samples were boiled for a long time with strong commercial HCl. The brown iron hydrate is very resistant, but can eventually be got rid of completely, leaving a white sand with a considerable amount of glauconite (variable in different samples, but always present); when wet this glauconite is of quite a bright green colour: when dry it usually becomes rather pale. In one sample from the northernmost quarry at Snettisham it remains very bright green even when dry.

This glauconite sand was then panned, and the heavy minerals separated in bromoform in the usual way. The result was an interesting and very characteristic mineral assemblage, which is worthy of a somewhat detailed description, since important conclusions can be drawn from it. An examination of a considerable number of specimens shows very close resemblances in all of them, so that one description will suffice.

The majority of the grains are rather large, and show much variation in the degree of rounding, rather more so than usual in rocks of this kind. The dominant minerals are kyanite and staurolite; the next group consists of tourmaline, rutile, and zircon; while garnet, pyroxene, and chloritoid are distinctly rare, though actually present in all, or nearly all, samples.

Kyanite is very abundant in large flakes and blades, usually very angular and showing frequently the characteristic "chopper" shape; occasionally the grains are more or less rounded, and even (very rarely) quite round.

Staurolite also is abundant in large grains, occasionally very angular, often more or less rounded, which is rather unusual in this mineral. The colour is some shade of yellow, sometimes bright orange, and pleochroism is well marked.

Tourmaline is generally very well rounded, occasionally prismatic in form, usually brown, rarely blue.

Rutile is rather common and shows all the usual variations of colour from orange to crimson. It is always perfectly easy to identify from its appearance in reflected light.

Zircon is somewhat less abundant than is usual in sandy sediments: the crystals vary much in size and some are pinkish in colour.

Pink or colourless garnet, sometimes well rounded, is distinctly rare.

Other minerals of still rarer occurrence are pyroxene and chloritoid. Blue amphibole, though carefully sought for, was found to be exceedingly rare; while monazite was not found, though carefully searched for. In a few specimens there were numbers of small mica flakes, but the occurrence of these is very sporadic.

This assemblage on the whole shows great similarity to the heavy minerals of the Carstone and of the Sandringham Sands described by myself in an earlier paper.[1] Messrs. Versey and Carter seem to have found more garnet than I observed in any of my samples.

PETROGRAPHY OF THE SANDY RESIDUE OF THE RED ROCK.

A detailed petrographical examination was carried out on two series of specimens, from the south quarry at Snettisham and from Hunstanton Cliff respectively. In the field these two sections are precisely similar, showing among other characteristics a division into bands, as before described, some nodular and some uniform, while on the whole the red colour becomes distinctly paler from below upwards, concurrently with an increase in hardness. The variation in colour is still more notable in crushed and wet specimens; however, even the highest bed when wet is very decidedly bright red, a peculiar shade of Indian red, which can by no means be described as pink. It is obviously due to anhydrous ferric oxide, a point which has some bearing on the problem of its origin.

The method adopted in the separation of the three components of the rock: the calcareous matter, the red mud, and the sand, has already been described.

Since it eventually appeared at a rather late stage in the work that the proportion of sand in the Red Rock at different levels might be a matter of some interest, a series of quantitative determinations were made. From each one of 8 specimens from the continuous section at Hunstanton 100 grams of material, as little crushed as possible, was weighed out and treated with acid as before described; the insoluble residues, after careful washing and decantation, were weighed, the figures being given in the following table. When plotted against the mean distance of the sample from the base, these figures give a fairly regular curve, which is shown in Fig. 1.

No.	*% Sand.*	*No.*	*% Sand.*
4	20·5	8	5·8
3	17·5	7	7·1
2	28·9	6	9·1
1	34·1	5	11·1

All specimens taken at distances of 6 inches, No. 1 being the lowest.

This sand is simply Carstone: it shows the same types of sand grains and rock chips, with the same brownish-yellow stain; the same glauconite; the same highly polished spherical black grains in approximately the same proportion, and the same heavy minerals after separation. Even the small mica flakes are occasionally, though rarely, found in large numbers. It would be impossible to determine, in the absence of a label, whether any particular one of the long series of specimens prepared came from the Red Rock or the Carstone.

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[1] Rastall, "The Mineral Composition of the Lower Greensand Strata of Eastern England," GEOL. MAG., Vol. LVI, 1919, p. 212. See also Versey and Carter, *Proc. Yorks. Geol. Soc.*, vol. xx, 1923–6, p. 349.

The heavy minerals have been separated from a considerable number of specimens, mounted and determined, but a description is unnecessary, as they are identical in every way with those from the Carstone, as before described.

Since the character of the insoluble residue and heavy minerals of the highest portion of the Red Rock, claimed by Messrs. Kitchin and Pringle as stained Chalk, is evidently a point of crucial importance, specimens from the last few inches at Hunstanton were treated with special care, and in particular the material was not put through a sieve, but dissolved in large lumps. In specimens taken only 3 inches from the top, the red mud fraction differed in no way, except in lesser relative abundance, from that below; the sand also was precisely similar in appearance to that from all other horizons. In another sample which was actually the highest 3 inches of the Red Rock, dissolved in large lumps without any sieving, the only difference from the last was in the presence of the flood of small mica flakes, which comes in at several different horizons throughout the Red Rock and in the Carstone: its presence merely serves to confirm their similarity.

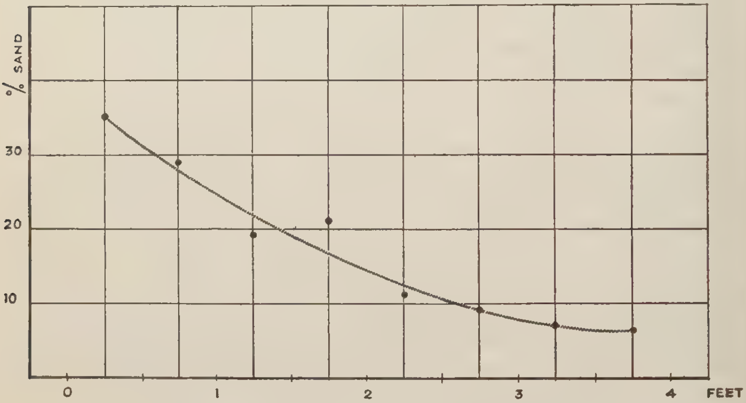

Fig. 1.—Percentage of sand in Red Rock.

The Petrography of the Sponge Bed.

In their paper in the *Geological Magazine* Messrs. Kitchin and Pringle, in dealing with the upper part of the Red Rock, write as follows: " We are of opinion that the top bed, 1 foot thick, which has not yielded any Gault Ammonites, should be regarded as forming the base of the Lower Chalk. It is a reddened lower part of the overlying " Sponge Bed ", which is not similarly stained. Except for the adventitious coloration of the uppermost red bed and the presence in it of minute polished black grains, there is close lithological resemblance between these two strata. Both have the same nodular aspect and are characterized by the same peculiar ramifying concretionary structures . . .[1]"

In view of my own observations of a marked discontinuity between the red and the white beds, which are separated by a variable seam of red material up to 2 inches thick, and the categorical statements of Judd and Wiltshire before quoted, it is clear that this problem required investigation.

As to the reference on palaeontological grounds of part of the Red Rock to the Lower Chalk I have nothing to say. My criticisms refer solely to the physical nature of the junction. From this point of view I naturally paid special attention to the petrography of the two layers in question.

Even during the process of solution of large specimens a point of some interest cropped up. The lumps of Sponge Bed developed what can only be described as very peculiar and characteristic etch-patterns: many surfaces showed conspicuous ridge and furrow patterns on a small scale; curiously enough the pattern was different on nearly every lump, and furthermore some surfaces showed nothing of the sort, remaining particularly smooth.[2] Several palaeontologists to whom the specimens were shown could recognize nothing organic in them, and they appear to be due in some way to the special concretionary nature of the Sponge Bed. There were only the vaguest indications of anything of the kind in lumps of the uppermost few inches of the Red Rock similarly treated.[3]

But the more important point concerns the character of the insoluble residue. Briefly, the residue from the uppermost bed of the Red Rock is identical with that from all other horizons in the same, whereas the residue of the Sponge Bed is entirely different.

The residue from the Sponge Bed is white, with a few concretionary fragments of a bright yellow ferruginous material, and colourless quartz grains. There is no trace of the brown stain on these grains. The fine mud removed on washing after the acid treatment was also of a pale creamy colour.

In the paragraph quoted above Messrs. Kitchin and Pringle say, referring to the uppermost part of the Red Rock and the Sponge Bed: "Except for the adventitious coloration of the uppermost red bed and the presence in it of minute polished black grains there is close lithological resemblance between these two strata." As a matter of fact the uppermost three inches of the Red Rock contain not only "minute polished black grains" as all the rest of this formation likewise does, but also many comparatively large pebbles of various kinds up to 3 mm. in diameter exactly like those found at all other horizons in it, in addition to the usual yellow-stained quartz grains. Their argument, implied if not directly stated, that the highest part of the Red Rock differs lithologically from the lower parts, cannot be sustained. Furthermore, the peculiar and characteristic heavy mineral assemblage persists up to the top of the red division, whereas the Sponge Bed contains no heavy minerals at all.

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[1] Loc. cit., p. 194.

[2] It should be made quite clear that the *same* lump may show surfaces of both kinds, ridged and smooth.

[3] See Hughes, 1884, in bibliography at end of this paper.

The insoluble residue of the Sponge Bed after the usual acid treatment shows some peculiar features. Except for a few specks of yellow iron oxide of box-stone type (which are not always present) the residue is nearly colourless, or very pale creamy white, and consists mainly of organic structures resembling foraminifera. If this is their nature it seems strange that they do not dissolve in 10 per cent acid. However, the really remarkable fact is that they are not dissolved by prolonged boiling in concentrated aqua regia, but remain as snow-white finely granular looking structures of pronounced organic appearance. In this condition they have a strong adsorptive power for organic dyes. Mr. A. G. Brighton has kindly examined this material for me and finds that many of the forms are arenaceous foraminifera, the cementing material being evidently silicified. This agrees entirely with the results of an examination of the Sponge Bed by Messrs. Jukes-Browne and Hill, who recognized in the residue from 20 per cent acid such forms as *Rhizammina*, *Haplophragmina*, *Ammodiscus*, and *Bulimina*. These authors also found no mineral grains other than quartz, minute rounded glauconites, and a little iron oxide.[1] This agrees with my results as to the complete absence of heavy minerals in the Sponge Bed. It is, I think, unnecessary to labour further the point that lithologically there is no resemblance between the top of the Red Rock and the Sponge Bed.

It is clear, therefore, that before the formation of the Sponge Bed the peculiar type of sedimentation characteristic of the Red Rock had entirely ceased. The supply of the Carstone type of sand, which had been gradually diminishing in amount, had come to an end, as had likewise the supply of red mud, and only calcareous precipitation continued. This implies a decided break in the physical conditions, and this break seems to be quite abrupt. It remains to consider the significance of the layer of red material now seen between the two formations, which is described both by Judd and Wiltshire, and is conspicuous in the cliff section. It varies in thickness from a mere line up to 2 inches and is of a very deep red colour ; it is quite soft and sticky. I am much indebted to Mr. G. G. Dorer, B.A., of Christ's College, for collecting additional specimens of this material.

The petrographical examination was an exceedingly tedious business, as it does not disintegrate in water, and can only be treated by very long-continued rubbing and washing. There is hardly any sign of effervescence with 10 per cent acid, which appeared to have no effect at all on the substance. However, 100 grams of the material eventually yielded 11·2 grams of clean residue free from red mud, which to the naked eye was very like the residue of the Carstone and Red Rock, though microscopically there is an important difference.

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[1] Jukes-Browne and Hill, *The Cretaceous Rocks of Britain*, vol. ii ; "The Lower and Middle Chalk of England," *Mem. Geol. Survey*, 1903, p. 295.

The heavy residue from the bromoform separation is remarkable and distinctive. To put it shortly, it contains the characteristic large-grained minerals of the Carstone and Red Rock, including especially the large kyanites and staurolites, but in addition to these there is a flood of much smaller grains of an entirely different mineral assemblage, characterized specially by the abundance of blue hornblende and colourless pyroxene.

The following list shows the chief minerals found in the red seam, divided into two groups, according to size.

Small type.
zircon
rutile
tourmaline
epidote
zoisite
garnet ?
pyroxene
blue amphibole

Large type.
kyanite
staurolite
garnet
tourmaline
rutile

One large rounded grain is undoubtedly monazite, but as some work on this mineral was going on in the laboratory at the same time it possibly got in by accident. There are certainly a number of other minerals present among the small grains, but this does not profess to be a full description of this assemblage; the object is merely to point out the sudden appearance of a new set of heavy minerals of quite different type. The flood of blue amphibole, pyroxene, and epidote, which are by far the commonest minerals present, is quite sufficient for this purpose.

It was hoped that by means of the curve shown in Fig. 1 and a determination of the percentage of sand in the red seam, it might have been possible to calculate the thickness of Red Rock removed by denudation before deposition of the Sponge Bed, but the petrographical examination of the red seam revealed the presence of so much material derived from some other source, that any such calculation must have been fallacious.

Since it was apparent that there is a resemblance between the red mud fraction of the Red Rock and the red seam at the top of it, a large sample of the red mud was collected by decantation, filtering, and drying. This and a sample of the red seam were submitted to Messrs. Bean and Brown, of Sunderland, for partial analysis. In the ignited material three constituents were determined, namely, total silica, ferric oxide, and alumina; the results were as follows.

	Red Mud.	*Red Seam.*
	%	%
SiO_2	42·84	39·79
Fe_2O_3	15·91	32·45
Al_2O_3	12·89	14·20

As a matter of fact these analyses do not really lead to any particular result, since the red seam contains over 11 per cent of sand and pebbles, the latter including a good many lumps of iron ore of various kinds. At any rate it is clear that there is a good deal of iron and alumina in both, and there appears to be nothing in the figures inconsistent with the idea that naturally presents itself on various other grounds, that the red seam is a solution residue of the Red Rock, with the addition of ferruginous material from some other source, i.e. as pebbles. This idea is confirmed by the sudden and remarkable appearance of a flood of wholly new and extraneous heavy minerals, as just described. The irregular and discontinuous character of the red seam suggests that it is a residual formation, and the presence of ironstone pebbles and an entirely new set of heavy minerals shows that it was not underground solution, but that it took place on the open sea-floor, as the result of a sudden alteration of physical conditions, bringing in materials from a different source, with a temporary stoppage of calcareous precipitation; in fact, a complete change in the concentration of the solution. After a while, however, calcareous precipitation began again, without any admixture of ferric and aluminous material, giving rise to the remarkably pure and very thin strata of the Lower Chalk of this region.[1] It is evident that some very remarkable geographical changes are here involved, and their relation to Prof. Bailey's conception of the desert shores of the Chalk sea yet remain for consideration. On account of the already inordinate length of this paper, this fascinating subject cannot be further pursued here.

However, if I may be permitted to put forward a bit of rather rash generalization, I would say that to my mind the facts here set forth suggest a sudden change at the base of the Cenomanian from normal damp conditions to desert denudation of an extreme type in the nearest land areas, wherever these may have been.

GENERAL CONCLUSIONS.

In considering the actual constitution of this peculiar deposit and its possible origin, some very difficult problems present themselves. Essentially the rock is a mixture of carbonates, red mud rich in ferric iron and alumina, and a brown highly ferruginous sand. It is at once apparent that iron exists in two totally distinct forms; as red anhydrous oxide in an extremely fine state of division and as a brown hydrated oxide of the usual wet-sedimentary type. One possible inference is that the anhydrous ferric oxide was introduced in suspension in a very finely divided and insoluble form, while the hydrated oxide was precipitated from solution in the ordinary way. Otherwise we are faced with the problem of the stability of both anhydrous and hydrated oxides under the same set of physical conditions, which on the face of it appears impossible in the light of well-known physico-chemical laws. But if the red anhydrous oxide can be considered as an insoluble disperse phase, it would have no influence on the equilibrium of the solution, and the situation becomes intelligible.

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[1] It is to be remembered that deposition of pink Chalk certainly continued in Lincolnshire and Yorkshire to a somewhat later date, but the distance from Hunstanton to the nearest Cretaceous outcrop in Lincolnshire is about 20 miles.

During the deposition of the sands of the Carstone we may suppose that hydrated iron oxide was being deposited as a cement and a coating on the grains. A subsequent infiltration of this iron seems to be excluded by the fact that the sands of the Red Rock are exactly similar to those of the Carstone: it is impossible to believe that solutions capable of depositing hydrated oxide penetrated into the Red Rock and stained all the quartz grains yellow, as well as giving rise to the formation of the black ooliths, while having no effect at all on the red mud and on the calcareous matrix. It is well established also that glauconite is a contemporaneous formation, and there is any amount of fresh glauconite in the Red Rock. This special type of sedimentation was therefore going on at the time of its deposition.

The source of the calcium carbonate is not a matter of much interest, since this can be brought about in many different ways, both organic and inorganic. From this point of view it is not unreasonable to regard the Red Rock as a variety of Chalk, using this term in the lithological rather than the stratigraphical sense.

At first sight it might be suggested as a simple explanation of this peculiar mixed deposit that the sand grains of Carstone type were derived: that is to say that the Carstone was undergoing denudation so that its constituents were transported and incorporated in the calcareous and muddy precipitate, but this presents difficulties. In the first place there is no physical break to be seen and the transition is gradual; but the more important point is that sand grains with a pellicle of iron oxide could not survive marine denudation and transport: they would be scrubbed clean by wave and current action, and there is no sign of this. The grains differ in no way at all from those of the undisturbed Carstone below. Furthermore the absence of any kind of sorting and grading in the Red Rock is very difficult to explain on any hypothesis. Grains of all sorts and sizes occur jumbled up anyhow at all levels, and yet it must have needed fairly strong currents to transport the larger ones. It is hard to see how the pebbles and large sand grains on the one hand, and the exceedingly fine calcareous and muddy material on the other, were deposited at the same time and in the same place. Any current strong enough to carry the largset pebbles should have washed away the fine material altogether. It really seems as if the physical environment that prevailed at the time of the formation of the Red Rock must remain a geological mystery, as the evidence is hopelessly conflicting. It is possible that further knowledge of sedimentation under tropical conditions may ultimately yield the key to the problem.

It is unfortunate that we have so little information as to the further extension of the Red Rock type of sedimentation to the south and east. H. B. Woodward has a somewhat vague remark that in places near Sandringham the Chalk Marl contains layers of a pale pink colour,[1] and it is particularly unlucky that we know so little about the boring at Holkham, where 8 feet of Red Rock was underlain by 10 feet of grey Gault.[2] It is evident from this that this particular type of deposit began earlier in the west than in the east of the area. Presumably the sea became deeper in the last-named direction, as it also obviously did towards the south, where grey Gault alone was deposited. The red type extended into Lincolnshire and Yorkshire at about the same date, though apparently in a less concentrated form, since the red rocks are there .of a much paler colour, and are usually called Red Chalk. The only place where I have actually seen it in Lincolnshire is near South Willingham, and there, according to my recollection of some 25 years ago, it is of a very pale pink tint. The base of the series in these counties shows an extensive overlap, and the zonal correlation of the red beds is as yet by no means certain, though there appears to be little doubt that they include some Cenomanian strata.[3]

In an earlier section it was suggested that the red material was introduced into the deposit in the state of a fine suspension, while the brown iron hydrate was precipitated from solution. Such a suggestion raises some large questions, which may be taken seriatim.

The ultimate source of the iron of the brown hydrate need not be discussed at much length. It is well known that the Lower Cretaceous strata of this country contain altogether a vast amount of iron. It is only necessary to mention the Wealden ironstones of Sussex, the ferruginous sands of the Lower Greensand of Southern England, and the Neocomian oolitic ironstones of Lincolnshire, in addition to the Carstone. All this iron must have been derived from the denudation of older rocks, and the clay-ironstones or the pyrite and marcasite of the Coal-measures at once suggest themselves as a possible source. However, in another section of this paper reasons are given for believing that the material of the Carstone did not come from the north.

This yellow-brown hydrate is just the type of iron compound associated with normal weathering in a moist temperate climate, where the iron somehow goes into solution in water, perhaps as compounds of organic acids, or perhaps as some form of iron sulphate: precipitates of it are well known in many streams in Coal-measure districts, e.g. around Sheffield. In fresh water the precipitation can be easily explained as due to oxidation, but recent studies of oolitic ironstones of marine origin have suggested that in the sea it may be of bacterial origin, as for example in the great work of Cayeux on the minettes of Lorraine.[1] This question is here introduced owing to the presence in both the Carstone and in the Red Rock of well-characterized ferruginous ooliths, as previously described.

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[1] H. B. Woodward, *The Geology of England and Wales*, 1887, p. 408.

[2] W. Whitaker, *Proc. Norwich Geol. Soc.*, pt. i, 1878, p. 16; R. H. Rastall, *Geology in the Field*, 1909, p. 152.

[3] Kitchin and Pringle, op. cit., p. 196.

With regard to the origin of the red material, Prof. Bonney long ago suggested that it was due to the decomposition of glauconite.[2] This explanation, which is attractive on the face of it, is ruled out by the fact that the Red Rock contains large quantities of perfectly fresh glauconite, which is only revealed by the treatment here adopted. Furthermore, none of the other numerous calcareous and glauconitic strata of the Cretaceous, and especially the Cambridge Greensand, show any similar red coloration. It seems evident, therefore, that the red mud must have been introduced into this deposit in its present form, probably, as already suggested, as a disperse solid phase in an extremely fine state of division.

Now there is in active operation at the present time a type of weathering which gives rise to exactly this kind of product, namely, the lateritic and bauxitic decomposition of rocks under special climatic conditions, essentially tropical or sub-tropical. The characteristic of this weathering is to produce not hydrated aluminium silicates (kaolinite) and iron hydrates, but ferric oxide and alumina, both probably in a colloidal form, with concomitant separation of soluble silica.[3]

This suggestion that the red material is of lateritic origin may possibly meet with the criticism that material must have been supplied to the Red Rock area of deposition from two different sources at the same time, but this objection is not insuperable : as a matter of fact it is clear that some of the rivers of the Malay Peninsula must be carrying down both kaolinitic and lateritic material at the same time, and probably dissolved iron as well, since there is much sulphide in the mineralized areas. It is easy to suppose that the laterite from which the material of the Red Rock was derived was not then in process of formation, but undergoing denudation, as some of that in Malaya probably now is. It may have some bearing on the point that much of the material that finds its way into the rivers from the tailings of Malayan tin mines is of a distinctly red colour, and this is after all only a kind of artificial denudation. The colour is almost identical with that of the bauxites of Antrim and Les Baux, for example, with a very strong resemblance to the red mud of the Red Rock when concentrated by acid treatment. For an example of transport of red material by a river under quite natural conditions it is only necessary to refer to the well-known instance of the Amazon. In a recent memoir on the geology of Ceylon Prof. F. D. Adams writes as follows in a description of the lateritic clay so abundant in that island: "The swollen streams running through these valleys in time of heavy rain carry their burden of clay out to sea, their waters being bright red in colour."[1]

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[1] Cayeux, *Les Minerais de Fer oolithiques de France.*

[2] Bonney, *Cambridgeshire Geology*, 1875.

[3] The voluminous literature of this complicated subject is admirably summed up by Dr. C. S. Fox, of the Indian Geological Survey, in his book *Bauxite*, London, Crosby Lockwood, 1927.

If this argument is accepted, it would seem to follow that at some horizon in the Cretaceous the supply both of suspended iron and alumina and of soluble iron stopped abruptly, but the occurrence of pink streaks here and there at higher levels in the Chalk, e.g. near Mildenhall[2] and at Isleham Waterworks[3] suggests a partial resumption of the process at later dates. The general cause of the stoppage was doubtless the beginning of the great Cenomanian transgression, which quickly flooded the land areas from which the material had hitherto been derived.

This conception of lateritic and bauxitic weathering on neighbouring land areas, setting free soluble silica, may have an important bearing on the origin of the silica of the Chalk, favouring the growth of siliceous organisms. However, it does *not* explain why in the upper part of the Chalk this silica aggregated itself into flints, while in the lower part it remained dispersed.

SOURCE OF THE MATERIAL.

A few words may now be said as to the source of the material of the Carstone and of the Red Rock from the geographical point of view. It is clear that the two formations must be taken together, since the brown sand is common to both. The former at any rate is obviously a deposit of very shallow water, since in parts it is conglomeratic rather than sandy. The chief constituent of the smaller grains is quartz, which proves nothing, but it is noteworthy that most of the larger pebbles appear to be cherty, and the same is true of the Neocomian rocks of Lincolnshire (Claxby, Donington). As already noted, a derivation from the Carboniferous of the Pennine area at once suggests itself, but on this point the study of heavy minerals has something to say. As before stated, the characteristic heavy minerals of both the Carstone and the Red Rock are kyanite and staurolite, while garnet is rare and monazite was not found, in spite of most careful search.

Now Prof. Gilligan has made an exhaustive study of the petrography of the Millstone Grit, in which he found that the characteristic minerals of that formation are garnet and monazite, with no kyanite or staurolite.[4] So far as I can ascertain, in default of published work on the subject, there appears also to be very little kyanite or staurolite in the Jurassic sandstones of Yorkshire, which were almost certainly undergoing denudation in Lower Cretaceous times. A supply of sandy sediment from the north and north-west could scarcely avoid including material from these formations, and the absence of the characteristic Millstone Grit minerals seems definitely to exclude derivation from the north. Messrs. Versey and Carter have dealt with this point: they find that kyanite and staurolite decrease in size and number northwards in Lincolnshire, and in the earlier stages of the Cretaceous were unable to pass the Market Weighton axis. Garnet on the other hand increases northwards. The complete absence of monazite from any of the samples examined by these authors and by myself definitely excludes derivation from the Carboniferous of Northern England.

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[1] Adams, "The Geology of Ceylon," *Canadian Journal of Research*, vol. i, 1929, p. 442.

[2] Jukes-Browne, GEOL. MAG., 1887, p. 24.

[3] Ibid., 1894.

[4] A. Gilligan, "The Petrography of the Millstone Grit of Yorkshire," *Q.J.G.S.*, vol. lxxv, pt. iv, p. 251.

It might perhaps be objected that the drastic acid treatment that has to be adopted to separate the heavy minerals from these rocks would destroy any monazite that is present, since this mineral is a phosphate and therefore possibly less stable than silicates like kyanite and staurolite. Most of the text-books, apparently copying from each other, state that monazite is attacked with difficulty by HCl. In order to investigate this point a sample of monazite sand from Brazil was digested for a long time with hot aqua regia, as used in the rest of this work. The effect was very slight, if any. In connection with the monazite question an experiment was very kindly carried out for me by Dr. W. A. Wooster, of the Department of Mineralogy, Cambridge, in order to test for the presence of any radio-active material in my specimens. Three samples of Carstone and Red Rock sands not treated with strong acid were placed on a photographic plate, together with a pinch of Brazilian monazite sand as a control. The plate was then kept in a light-tight box for a week. On development it was found that the Brazilian monazite grains had made very distinct images, while there was no trace of any radio-active effect from the Norfolk sands. It may, I think, safely be concluded that there is no monazite in the Cretaceous sands at Hunstanton. I am much indebted to Dr. Wooster for his help and advice in this matter. Further the great scarcity of garnet also helps to disprove derivation from the Millstone Grit of Northern England, where Prof. Gilligan found it so common. As regards the Jurassic sands of Yorkshire, according to my limited experience of these, anatase is a very common constituent, and so far as I am aware this mineral has not been recorded in Norfolk.

Messrs. Versey and Carter suggest as a possible source of the material one or more of the Charnoid axes in the Midlands as worked out by myself in previous papers in this Magazine. A first-sight objection to this idea is the improbability of any metamorphic rocks with kyanite and staurolite being brought to the surface by Charnoid uplifts in this area, since such are not known to occur anywhere in England. It seems clear that the derivation cannot have been at first hand, but there is no reason why sediments exposed by such uplifts should not have contained these minerals at second hand. It is unfortunate that we know so little of the heavy minerals of the older Palaeozoic rocks.

There remains, however, another possible source, namely, the ancient plateau of London and Brabant, which is of so great importance in controlling the limits of the subsequent formations of England, Belgium, and Holland. We know that this includes normal fossiliferous Lower Palaeozoic rocks, both in England and in Belgium; but we do not know what else it comprises: at any rate it is certain that this plateau was exposed to denudation up to the end of Lower Cretaceous times, and in England at least was finally submerged under the waters of the Albian sea, whereas Aptian strata are absent in most of the borings which have reached it.[1] The final closing of this source of material was undoubtedly the dominant factor in explanation of the abrupt change from mixed sedimentation to Chalk at the outset of the Cenomanian.

SUMMARY.

At Hunstanton Cliff and at Snettisham there is a gradual transition, without physical break, between the Carstone and the Red Rock. At Hunstanton there is a physical break, marked by a solution-surface, between the Red Rock and the Sponge Bed. At Snettisham the Red Rock is incomplete at the top.

The Carstone shows a peculiar and characteristic assemblage of mineral constituents, with much glauconite and ferruginous ooliths. The heavy minerals are notable for the abundance of kyanite and staurolite and rarity of garnet.

The Red Rock consists of three fractions: (*a*) calcium carbonate, (*b*) red mud, (*c*) sand. This sand is exactly like the Carstone, with the same heavy minerals, and it continues, though in diminishing amount, up to the very top of the Red Rock.

The insoluble residue of the Sponge Bed is entirely different: it consists mainly of silicified foraminifera, with a few colourless quartz grains, and it contains no heavy minerals at all.

There is an abrupt and complete lithological change at the base of the Sponge Bed.

The red fraction of the Red Rock is rich in Fe_2O_3 and Al_2O_3, and it is suggested that it is of lateritic origin.

The precise manner of formation of the Red Rock is not explained. It has not been found possible to visualize a set of conditions under which fairly large pebbles, ferruginous sand grains, ferruginous ooliths, red mud, and calcium carbonate were all deposited at the same time.

It is suggested that the red mud is due to lateritic material derived from a neighbouring land area.

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[1] Full references to the extensive literature are given in my earlier papers in this Magazine, Vols. LXII, 1925, and LXIV, 1927.

The heavy mineral assemblage shows that the material of Carstone type did not come from the north, and probably not from the west. The only possible source is the Caledonian and Armorican plateau of London-Brabant or a continuation of it under the North Sea. The sudden change at the top of the Red Rock is due to the submergence of this land area by the Cenomanian transgression, which in Norfolk was accompanied by local erosion: this finally closed the source of supply of the heavy minerals: here and there a slight recurrence of transport of lateritic material gave rise to pink bands in the Chalk at higher horizons.

The interpretation by Messrs. Kitchin and Pringle, on palaeontological grounds, of the relations of the Red Rock to the Carstone and to the Chalk is shown to be quite inconsistent with the results of this petrographical investigation.

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The Loess Problem of China.

By George B. Barbour, Ph.D., F.R.S.E., F.G.S., Yenching University, Peking.

The Problem.
Outline of post-Mesozoic Geological History.
Red Clays of the Paote Stage.
Deposits of the Sanmen Stage.
Deposits of the Malan Stage.
Deposits of the Panchiao Stage.
Recent Deposits.
Origin of the Loess.
Delimitation of the Loess.
Faunal Associations and their Significance.
Age and Correlation of the Loess.

Summary.—An analysis of the Loess problem is made on the basis of recent studies co-ordinating results of research along a variety of lines. Sources of confusion in the past are indicated, and the question of the delimitation of the term "loess" is discussed.

In China the Loess is essentially an aeolian deposit formed under special climatic conditions which ruled, though in different degrees, at two distinct epochs in the Pleistocene period that seem to correspond to the Günz-Mindel and Riss-Würm twin-glaciations respectively. The variations in the deposits and the relation between them, the associated fresh-water sediments, and recognizable stages in the physiographic evolution of the landscape are described. The character and implications of the fossil content are discussed, especially in their bearing on the problems of former climates and of exact correlation of geological events.

The Problem.

For fifty years the loess of China has presented a geological problem of the first rank. Since the days of von Richthofen much has been written in attempts to explain its presence and its characteristics. Sharply divergent opinions have been expressed as to its origin, age, and mode of accumulation. It is only recently, however, that critical study has yielded data from a sufficient variety of angles to circumscribe some of the problems involved. By a concerted attack along many lines—combining the results of lithological study, fossil evidence, and stratigraphic and structural relationships with physiographic and climatic considerations—an advance towards a reasonable explanation of the facts is now possible. Final solutions of many details are not yet in sight, but a point has been reached where the air will be cleared by a statement of the main conclusions thus far attained and of the aspects of the problem calling for further study.[1]

The dilemma in the situation lies in the fact that the term " loess " has been applied to a whole group of deposits of at least four distinct geological ages, ranging from Lower Pliocene to Recent, and including everything from conglomerate and talus material to silt, dust, and residual clay. The various facies at times overlie one another with sharp contact, but often intergrade vertically or horizontally without clear line of demarcation. Many pictures shown of supposedly typical loess-scenery in Shansi are actually of dissected Quaternary lake deposits with only a 6- or 8-foot veneer of true loess.

At first sight the problem might seem to be largely one of terminology. But it is too complex to be solved merely by more careful definition of words.

In theory the natural procedure would be to restrict the term " loess " to deposits of a definite lithological type. In practice this proves extremely hard, because the intimate association and intermingling of the various types of sediment makes it impossible to be strictly consistent in delimiting any one facies. Moreover, taken as a whole, the loess *sensu stricto* represents a distinct set of climatic and physiographic conditions which held sway over a wide area, and the term has been an established formational name since the days of von Richthofen and Pumpelly. And yet, as already noted, the word is commonly used to cover at least four formations separated by three important erosion intervals.

On the other hand, the simple plan of giving provisional locality-names to every unit in each new area studied, while logical and scientific, leads to a multiplication of terms that is really unnecessary. For one feature of these formations, even where showing wide range of facies, is the constancy of their stratigraphic position and structural relationship to each other, and of their association with characteristic geomorphological conditions, even in widely separated districts.

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[1] An attempt was made to clear the ground for this study by a preliminary paper, " The Loess of China," *China Journal of Sc. and Arts*, vol. iii, 1925, pp. 454–63, 509–19, and vol. iv, 1926, p. 46 (reprinted in a slightly abridged form in the *Smithsonian Annual Report* for 1926).

The region involved lies between the Mongolian border and the Yang-tze-kiang, extending over the northern provinces of Kansu, Shensi, and Shansi, and including ithe north-west parts of Manchuria and Hopei Province (formerly Chihli) with much of Chahar and Jehol. Many of the features noted extend also to northern Honan and Shantung.

The clearest understanding of the problem will be gained from a brief outline of the stratigraphic and physiographic history, before analysing some of the elements in greater detail.

OUTLINE OF POST-MESOZOIC GEOLOGICAL HISTORY.

1. The early Tertiary land-surface was reduced to one of low relief. The presence in some districts of gravel fans shows that spasmodic uplift kept the surface unsubdued locally, but over wide regions a peneplane was developed. This is the *Peitai* surface of Willis, which with its monadnocks is still preserved in the summit lines of many mountain districts.[1] (See block-diagrams.)

2. Block-faulting and warping in late Oligocene and early Miocene times—the intracontinental counterpart of the Himalayan or Nanling Revolution—accompanied by outpourings of plateau basalts along the Mongolian frontier, disrupted this surface, giving the streams fresh energy. This *Tanghsien Stage* proceeded to maturity, thus carrying a second cycle of erosion to an advanced point. Upon the new surface thus developed deposits began to collect, in places residual, elsewhere colluvial, stream-laid in the valley bottoms. Where fossiliferous they carry mammal remains of Pontian type. They form the oldest member of the group of superficial deposits often loosely included under the term " loess ". Till now the stage of aggradation to which they belong has not had a distinguishing name, but it may well be termed the *Paote Stage* in view of the great development of deposits of this epoch near Paote on the Yellow River in eastern Shansi.

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[1] The physiographic stages discussed in these five paragraphs are treated in greater detail in :—

G. B. BARBOUR. " Geology of the Kalgan Area " : *Geol. Surv. China Mem.*, A 6, 1929, pp. 94 ff., 148*a* ff.

The evidence for the various stages will be found in the following :—

J. G. ANDERSSON. " Essays on the Cenozoic of Northern China " : *Geol. Surv. China Mem.*, A 3, 1923, pp. 107, 117, 129.

G. B. BARBOUR. " Deposit and Erosion in the Huailai Basin " : *Bull. Geol. Soc. China*, vol. v, 1926, pp. 27 ff.

BARBOUR, LICENT and TEILHARD. " Geological Study of the Sangkanho Basin " : *Bull. Geol. Soc. China*, vol. v, 1927, pp. 263 ff.

TEILHARD and LICENT. " Observations géologiques sur la bordure occidentale de l'Ordos " : *Bull. Soc. Géol. de France*, t. 24, 1924, pp. 67.

TEILHARD and YOUNG. " Pre-loessic and post-Pontian formations in western Shansi " : *Geol. Surv. China Mem.*, A 8 (in press).

WILLIS and BLACKWELDER. *Research in China*, vol. i, pt. 1, Washington, 1907, pp. 237 ff.

L. F. YIH. " Geology of Hsishan " : *Geol. Surv. China Mem.*, A 1, 1920, pp. 66, 73.

3. Rejuvenation due to uplift in Pliocene times led to the vigorous dissection of the *Fenho Stage*, which destroyed much of the round contouring of the Tanghsien surface, especially its lower slopes. The major streams had again graded their channels and begun to widen their valley-floors when erosion gave place to aggradation towards the close of the Pliocene. The result was the accumulation of thick deposits of lake and river sediments flanked by fans of detritus of all kinds, including much reworked material from the Paote clays and gravels. Especially in the upper levels, wind-blown material was incorporated. The deposits of this epoch are at present grouped together as those of the *Sanmen Stage*,

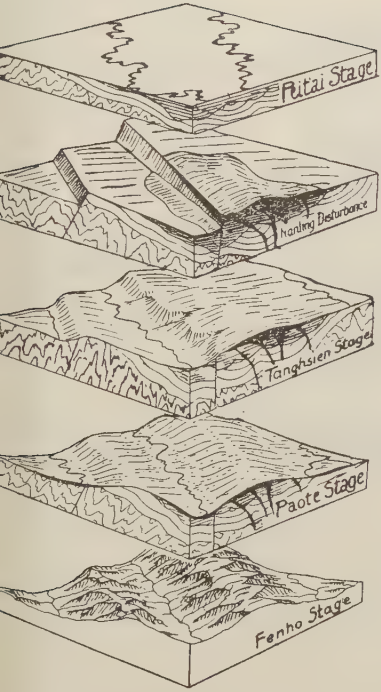

FIG. 1.

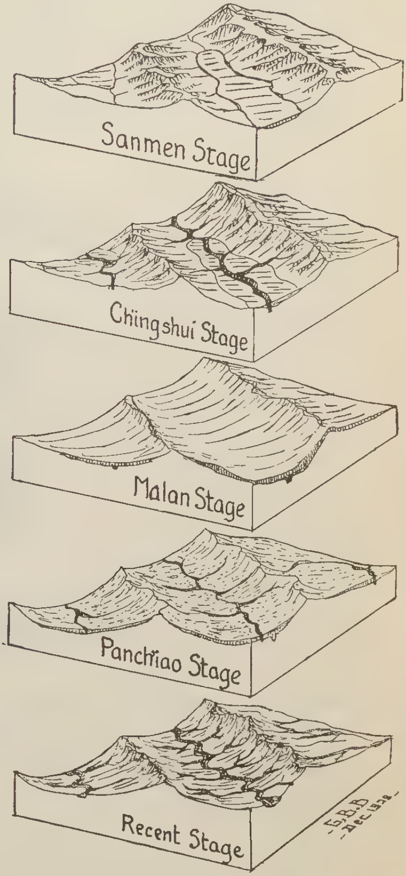

FIG. 2.

though subdivision may become possible with further data. Here belong the deposits of the Choukoutien cave in which *Sinanthropus pekinensis* was discovered.

4. A further rejuvenation followed in Lower Pleistocene times. The erosion of this *Chingshui Stage* trenched the Sanmen deposits, in some cases merely cutting gullies or gorges in them, elsewhere removing the bulk of the material. Under the influence of climatic change in Middle Pleistocene times erosion once again gave place to deposition—the *Malan Stage*—this time largely of fine wind-transported dust. This is the genuine loess, though it also shows variations in facies and in its basal layers incorporates reworked local material.

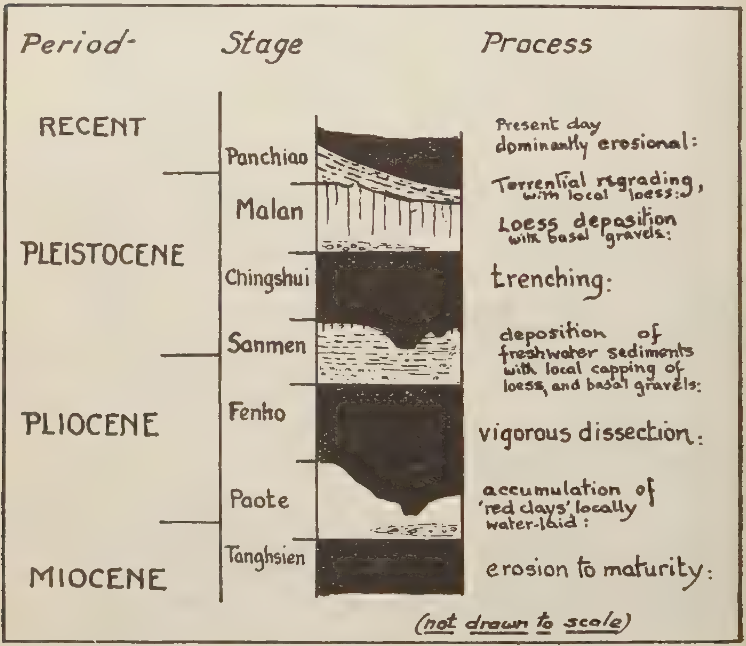
Period-
Stage
Process
RECENT
PLEISTOCENE
PLIOCENE
MIOCENE
Panchiao
Malan
Chingshui
Sanmen
Fenho
Paote
Tanghsien
Present day dominantly erosional:
Torrential regrading, with local loess:
Loess deposition with basal gravels:
trenching:
deposition of freshwater sediments with local capping of loess, and basal gravels:
vigorous dissection:
accumulation of 'red clays' locally water-laid:
erosion to maturity:
(not drawn to scale)

Fig. 3.

5. Return of moister conditions caused the *Panchiao Stage* of dissection which led up to the conditions of to-day. For a time surface water vied with high winds as transporting medium, giving rise to a composite formation of loessic material and gravels which Andersson termed "Redeposited Loess".

Finally, there are the present-day alluvial deposits in which much of the loessic material reappears again as silt. This is merely a local phase of the conditions of to-day which are dominantly erosional.

There is thus record of five erosion cycles, four of them involving deposits which conform to distinctive pre-existing sculpture-surfaces, and which in the nature of the case are often superposed, are progressively liable to contain reworked material taken from older surface-deposits, and hence are at times extremely hard to differentiate. In both popular and scientific writings the term "loess" is often applied without discrimination to any or all of them where sufficiently developed to attract attention. This practice is clearly inadmissible, since the word at once degenerates to mean any fine-grained unconsolidated sediment. And yet, even with our newer understanding of the character and range of the various groups, it is extremely hard to know just how to restrict the use of the term.

It will have been noticed that I have thus far carefully avoided any exact definition of *loess*. For myself I confine the use of the term for China to the fine-grained non-stratified loam deposits which develop a rudely prismatic, vertical cleavage; and since careful study establishes the fact that in China such material is essentially wind-blown, the definition carries an implication of aeolian origin. The same material where water-borne is just *silt*, and there is no reason why the term should be extended to this except in cases where a deposit is so dominantly loessic that, even with the presence of a few layers of silt or gravel, it still shows the typical vertical cleavage as the outstanding feature of the whole. Accepting this definition it is found that the great unadulterated development of genuine loess was during the Malan Stage and that, apart from this, loessic deposits only figure as minor constituents of the closing phase of the preceding Sanmen Stage. As will be shown below, I feel that in practice there is justification for extending the term Loess Formation[1] to the entire Malan unit, of which the loess forms the major and characteristic part, wherever it can be separated with certainty from older and younger deposits, irrespective of its facies locally. But this can better be appreciated after describing the deposits and their structural relationships in slightly greater detail and deducing from their character the probable conditions under which they formed.

RED CLAYS OF THE PAOTE STAGE.

Andersson was the first to note that the colour-contrast of the red-brown material at the base of the yellow-grey loess corresponded to a distinctly older formation. Some of the sub-loess sediments yielded a typical Hipparion fauna. Further work by Zdansky[2] confirmed his conclusions and recent work by Teilhard, Licent,

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[1] As a further distinction, where used as a formational name it should be capitalized (*Loess Formation*) to distinguish from *loess*, the material, considered irrespective of its geological age.

[2] Andersson, op. cit., p. 107.

Young, and others show that the formation is widely extended over North China and south-east Mongolia.[1] At one time it must have covered practically everything except the higher mountain surfaces north-west of the Yellow River delta.

The colour of the " red clay " is usually a rich brick-red which deepens to a dark red-brown when damp. The vertical cleavage typical of loess is absent. The material is far from being a pure clay, being often more akin to a ferruginous residual earth ; but in contrast to the loess its clayey consistency is a distinctive feature. For instance, in parts of Shansi certain sections of the high roads are noted for their slippery or impassably sticky condition after rain, and these usually prove to be stretches where the trail, elsewhere on loessic or sandy terrain, crosses outcrops either of this formation or of the next younger one, which also has a clayey facies.

The Pontian fossils, by which certain units within the formation are dated, tend to occur in the associated freshwater beds. As a third facies, gravels conforming to the same topographic subsurface are noted in many places.[2]

In most of the areas studied, the Tanghsien land-surface on which the deposits accumulated was subsequently warped or uplifted. Hence in enclosed mountain basins the deposits are apt to be found at some height above the present stream-levels. But in the broad rift-valleys of Shansi and northern Hopei and along the margin of the subsiding Yellow River delta-plain the same type of deposits may be the lowest formation exposed.

A common feature both of the red clays and of the overlying Sanmen deposits is the presence of large calcareous concretions[3] which tend to form at certain horizons, often round a nucleus of fossil material.

Deposits of the Sanmen Stage.

First noted by Ting near the rapids of the Yellow River, then found by Andersson farther downstream,[4] deposits of this epoch are now known[5] to have been spread over an area comparable to that of the Paote deposits, but extend down to the base of the entrenched valleys of the Fenho erosion cycle. The facies first to attract notice were fluvio-lacustrine beds, some of which had been mapped by von Richthofen as " Seeloess ".[6] It was then seen that the formation passed laterally into poorly stratified outwash fans of pluvial breccia mixed with earthy material of a terra-cotta tint.[1] In the Sangkanho basin it was also noted that in the higher horizons there is an increasing proportion of fine non-stratified earthy material with an imperfect vertical cleavage, resembling an impure loess. Teilhard and Young subsequently found that this loessic facies is widely developed in Shensi west of the Yellow River. Though calling it the Yulin Formation in one district, they refer to it in general as "Reddish Clay" (argile rougeâtre) since its terra-cotta colour lies between the brick-red of the Paote clays and the yellow-grey or bleached khaki of the Malan loess. In fact, in much of its most typical development the formation is intermediate between these two others both in colour, texture, and consistency. The description occasionally heard—"red loess" —seems usually to refer to this facies and, as already noted, much so-called loess country is mainly Sanmen terrain. The older Paote Clays unquestionably contributed largely to these deposits, accounting for the red element in their colour. The basal gravels of the Sanmen Series are sometimes made up of little else than rewashed concretions clearly derived from the subformation, since originally the concretions in both formations are disseminated.

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[1] *Bull. Geol. Soc. China*, vol. vi, 1927, p. 129.

[2] Yih, op. cit., p. 64. Barbour, *Geology of the Kalgan Area*, p. 101. Teilhard and Licent, *Bull. Geol. Soc. China*, vol. vi, 1927.

[3] von Richthofen speaks of these as diagnostic of the Loess.

[4] Andersson, op. cit., p. 118, 119.

[5] Barbour, *Huai-lai Basin*, p. 47.

[6] v. Richthofen, *China*, Atlas. Barbour, " Deposits of the Sangkanho Valley," *Bull. Geol. Soc. China*, vol. iv, 1925. p. 53. E. Licent, " Voyage aux terrasses du Sangkanho, "*Mus. Paiho Hoangho*, Tientsin, pub. No. 4, 1924.

DEPOSITS OF THE MALAN STAGE.

Above the Sanmen deposits come the true loess and allied sediments of the Malan Stage. The Chingshui erosion, which removed vast amounts of Sanmen material, left a deeply dissected topography much like that of to-day. The loess is overlaid upon this surface like a veneer, conforming to the general contouring, but filling up the small gullies and canyons, and rounding out the angularities of the subsurface. In addition, the aeolian origin of the loess led to the incorporating in its lowest layers of much reworked local material from the underlying formation. Hence at many points the transition is so gradual as to defy demarcation of the two units. As a result of the character of this merging of the two formations, the thickness of the loess, especially east of the Yellow River, has been exaggerated for the following reasons:

1. The absence of a sharp contact-surface gives the false impression that the Sanmen beds are part of the Loess Formation.
2. Through failure to visualize the dissected floor on which the loess came to rest, the differences in elevation between the top and bottom (measured up slopes on continuous outcrops of loess) are taken to represent actual vertical thickness. (This is as fallacious as saying that the soil covering the top of a 400-foot hill must be 400 feet deep, or that the members of an audience in the back rows of an amphitheatre must all be over 10 feet tall.)
3. Owing to the absence of obvious contact, the vertical thickness of undoubted loess filling gullies cut in the Sanmen deposits is taken as the thickness of the Loess Formation as a whole.

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[1] Barbour, Licent and Teilhard, "Geological Study of the Sangkanho Basin," p. 265.

4. The Loess, as the superior formation, caps the older deposits and is carried down by rain over their outcrops, completely colour-washing them and giving an exaggerated impression of its own depth.

West of the Yellow River the loess thickens, attaining depths of 200 to 300 feet. The figures of 600 given by Andersson and Cressey were calculated before the character of the Sanmen deposits was known, and may on further study prove excessive. Certainly the older reports of "thousands of feet" include much besides loess.

In an earlier paper[1] I have reported at length on other characteristics of loess, including the questions of grain-size, mineral and chemical composition, water-absorption capacity, etc. As I hope later to give details of further studies now in progress, it is unnecessary to repeat those here.

Like the Sanmenian deposits, those of Malan age show a threefold development, but in very different proportions: (*a*) a coarse conglomerate facies, essentially restricted to the base of the loess; (*b*) a fluviatile facies, sandier and more apt to be fossiliferous; and (*c*) the non-stratified loess, which forms by far the most important element in the group. In addition, Teilhard has called attention to a distinct difference in quality between the loess proper of China which is fine-grained, and the coarse loess of the Mongolian border which is more sandy, actually passing into sand-dunes in many districts of the Ordos and Eastern Gobi.[2] Besides the Mongolian and Chinese facies he distinguishes also a Manchurian type intermediate between the other two. It might be added that the essential equivalence of these varieties is established by fossil evidence.

Finally, passing from the interior towards the maritime zone round the Gulf of Peichihli where the loess thins out rapidly, evidence of reworking by water-action is apparent, gravel and pluvial breccia are found interlayered, and in general the formation begins to lose its identity.

All these variations in the character of the loessic deposits have an important bearing on the problem of their origin. Indeed, it seems that their very variety itself confirms the interpretation offered below. First, however, the remaining stratigraphic history must be outlined briefly.

DEPOSITS OF THE PANCHIAO STAGE.

The loess itself, together with all the older superficial formations is in many places seen to have been cut right to the base, the erosion-surface being overlaid by still younger deposits of interlayered pluvial breccia, gravel, sand, and loess which fill gullies cut in the underlying deposits, or lie like a veneer over them.

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[1] "The Loess of China," *China Journal of Science and Arts*, vol. iii, 1925, pp. 454–63, 509–19, and vol. iv, 1926, p. 46.

[2] P. Teilhard de Chardin, "Étude géol. sur la region de Dalainoor," *Mem. Soc. géol. de France*, No. 7, t. 3, fasc. 3, 1926, p. 49.

The stream rejuvenation responsible for the dissection was due primarily to climatic change towards greater moisture and led up to the present-day conditions in which erosion is dominant. But the presence of these mixed deposits (which locally yield fossils of an age distinctly younger than the Malan loess) shows that the transition was a fluctuating rather than a simple direct one. Before the establishment of the present climatic conditions, torrential water-action alternated with high winds as an agent of deposition. Material previously deposited was reworked and shifted to new resting-places mixed with local detritus. On account of the lenses of such derived or secondary loess Andersson refers to the formation as " Redeposited Loess ".[1] The term is not altogether a fortunate one, since most loess has doubtless settled and been shifted several times before coming to rest and is therefore " redeposited " in any case ; whereas if the connotation of water-action is intended the use of the word " loess " may be challenged unless the term is to be extended unlimitedly to silts and fine sediments of all kinds.

The bulk both of the Loess and of this Redeposited Loess Formation is barren of fossils and in the absence of such criteria it is often impossible to be sure which formation is represented. This is especially true in the maritime zone where the moister conditions, typical of the Panchiao Stage in inland districts, ruled also, though less completely, in Malan days. I am inclined to think that the importance of the Redeposited Loess has been exaggerated and that it represents virtually the first regrading consequent upon the swing back from dry to moist conditions under sharply contrasted seasonal changes during the early stage of a new erosion cycle.

Recent Deposits.

Especially in mountain-girt basins where barriers at the points of outflow govern the local base-levels established further upstream, the recent flood-plains are apt to be terraced. As the material which builds these terraces has been largely derived from the older superficial formations, a further source of confusion is introduced. These terraces, however, are essentially low-lying and closely related to the present stream channels.

Origin of the Loess.

Confining attention first to the deposits of the Malan Stage, the following facts seem to confirm the aeolian origin advocated by von Richthofen for the loess proper :—

1. The loess itself is non-stratified. It is found on mountain faces directly overlooking the great delta up to elevations of 200 feet and more above the plain below, and in the mountain basins it

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[1] Andersson, op. cit., p. 129.

extends up the flanking slopes to heights of from 500 to 1,000 feet above the valley-floors. There is no evidence that the valleys were once filled level with sediments to such altitudes.

2. On the contrary, the loess-blanket clearly conforms closely to the general contouring of the buried pre-loess topography, filling up the gullies, covering the minor elevations, lying deepest in the depressions and thinning-out up the flanking slopes of the higher ridges.

3. Gravels of Malan age, if present at all, occur at the base of the loess and then only in erosion depressions cut in the sub-formation along lines which obviously correspond to former watercourses.

4. In many localities there is no sharp contact between the loess and underlying deposits which are known on lithological, palaeontological and physiological grounds to be of distinctly greater age. Instead the gradual transition points to a progressive intermixture of new with old material. A similar incorporation of derived material from an older formation, attributed to the winnowing action of wind, is cited by Schlosser[1] from the Miocene "Flinz" near Munich.

5. The thickness of the Malan deposits decreases steadily from the hinterland of Kansu and the Mongolian border towards the coast; at the same time, evidence of reworking by water increases on entering the maritime zone.

6. Passing in the reverse direction the texture of the loess becomes sandier on approaching the Mongolian border, and locally even passes into sand-dunes of the same age. Across the frontier typical loess becomes almost non-existent.

7. The winter-storm winds to-day in North China are from the north-west, are cold and extremely dry, and whenever strong are the cause of severe dust-storms usually lasting two or three days. At such times the higher air is charged with dust so that the whole sky becomes dusky and the sun turns a sickly green. Very rarely precipitation following such high dust-storms brings down the floating sediment from the upper air; when studied, this material proves to be indistinguishable from the material forming the loess.[2] Taken together, the facts point to climatic conditions under which the present winter-distribution of pressure was more dominant, and the summer monsoon effect perhaps less far-reaching, than is the case to-day. Strong winds blowing out from the Mongolian anticyclonic centre, drove before them the disintegrated material derived from the poorly consolidated Mesozoic and early Tertiary basin-sediments of the Gobi. The coarser fraction was swept over the flat floor of the plateau to drift into the dune-belt or come to

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[1] Max Schlosser, "Tertiary Vertebrates from Mongolia," *Pal. Sinica*, ser. C, vol. i, fasc. A 1, 1924, p. 104.

[2] G. B. Barbour and C. J. Wu, "High Altitude Dust at Peking," *China Journal*, vol. vii, 1927, p. 3.

rest in the rapidly desiccating depressions along the Chinese frontier. The finer stuff was wafted out over the valleys and dissected ranges under the lip of the plateau, dropped and caught up again, mixed with material of the locality, and shifted again till finally brought to rest and fixed by such growing vegetation as the little available ground moisture could keep alive on the margin of the steppes.

Shaler has given a vivid description of the process as he watched it taking place in Montana :—

> The conditions of the formation of this loess deposit may be observed at any time when the earth is dry and the wind strong enough to lift the dust, as is the case for a considerable part of each year. From the surface of the benches of the valley, as well as from the scantily vegetated lower parts of the mountain ranges, dust is blown to and fro in large quantities. So long as it encounters no closely set vegetation it does not come to rest. It is only when it finds its way amid densely set plants in the limited areas watered by snow-fed streams that it escapes from the controlling wind. In such places it is quickly fixed, to remain so long as the natural or artificial irrigation continues.[1]

Analogous conditions were noted by Willis in his study of the *mallins* or swampy meadows of Patagonia. The deep deposits of extremely fine soil are largely composed of wind-blown dust mixed with humus ;

> The flying dust is caught by grasses and other plants, or on bare spots is held by moisture . . . Plants quickly spring up on a layer of fine soil . . . helping to retain the moisture by catching more dust . . . When with the change of seasons the waters dry out, the soil settles, compacts and becomes hard.[2]

Two further points seem to fit in with the picture of the climatic conditions given above.

One is the general character of the fauna, which is a *cold* fauna, in contrast to the *warm* association of the Late Pliocene and early Pleistocene Sanmenian types.

The other significant point is the human aspect of the case. Teilhard and Licent found Palaeolithic implements of a quasi-Mousterian type on the southern border of the Ordos;[3] other localities have been reported since. The *foyers* seem to be concentrated in the horizons near the base of the loess, usually in intercalated river-gravels whose absence from higher levels in the formation unquestionably indicates drying up of the streams. Above the basal horizon, the loess is barren of all further sign of culture. Indeed, no further traces of human occupation recur in the region until the abrupt appearance of the Mesolithic in Mongolia followed at a still later date by the various stages of Neolithic culture widespread over China. Evidently the coming of the loess marked the onset of rigorous conditions too severe for human life, especially on the exposed steppe lands of the frontier.

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[1] N. S. Shaler, "Loess deposits of Montana, *Bull. Geo. Soc. Am.*, vol. x, 1929, p. 246.

[2] *Northern Patagonia,* Scribners, New York, 1914, p. 106.

[3] "Le Paléolithique en Chine, " *l'Anthropologie,* t. xxxv, 1925, p. 201.

If the picture of conditions has been correctly drawn, the gravels of the Malan epoch represent the first stage of aggradation caused by the drying up of the Chingshui streams and the failure of the surface waters. With the gradual extension of semi-arid conditions, the loess spread over wider areas. For a time standing water or intermittent streams might still be found in more favoured depressions but for the most part all the rain that fell was absorbed by the ground. In the maritime zone, however, relatively moister conditions could still persist so that the dust was laid sooner and travelled less ; sediments were rewashed and mixed with pluvial breccia.

DELIMITATION OF THE LOESS.

Three major stages of aggradation were noted—the Paote, Sanmen, and Malan Epochs. The first shows no deposits of true loessic character. With regard to the deposits of the Sanmen Stage, however, it was noted that in the upper levels a certain amount of loess-like material is locally present. This facies develops extensively west of the Yellow River in Shensi, but in general forms a very minor proportion of the entire formation and, even though without doubt it lost more by direct erosion and by incorporation in the Malan loess than did the underlying fluviatile member of the Sanmen group, it very evidently never attained the relative importance that the loess holds in the Malan deposits. It is impossible to say at present whether or not in actual bulk this Sanmen loessic red clay ever equalled the volume of the Malan loess. Certainly it seldom if ever attains the characteristic constitution of the latter. It seems invariably more earthy and clayish, so that Teilhard's generic name " reddish clay " is not inappropriate. Vertical cleavage is much less perfectly developed and the colour never attains the freedom from reddish tint of the yellow-grey loess. How far these differences are original and how far a subsequent effect of secondary changes is not clear. The concretions suggest considerable later chemical action.

The question then arises, how should the term " loess " be used ? Since the word has passed into common currency with an unduly extended meaning, can any scientific restriction be attempted, or must the question be solved by introducing new terms, leaving the word loess to cover its heterogenous assortment of sediments ? Any restriction in use must avoid violating common sense by being too exclusive. On the other hand, too inclusive a term will suffer the fate of Willis's excellent formational name *huang-t'u* (at once a locality name and the Chinese name for loess, " yellow earth ") discarded since it was found to include the bulk of the deposits of three, if not four, epochs.

As a practical measure, pending confirmatory study over still wider unexplored areas to the west, I return to the distinction given above. The word " loess " can properly be applied to the major element of the Malan deposits, and by a natural extension the term Loess Formation can be used of the slightly larger unit of which it is the significant part. The term loess can also be used of deposits of the concluding phase of the Sanmen Stage, but cannot legitimately be extended indefinitely downwards to underlying members whose material is distinct in character and was laid down at an earlier date under different conditions. Where a distinction is called for one may distinguish the Malan loess from the Sanmen loess, though in the latter case the terms "reddish clay" or "earth" would often be a truer description.

FAUNAL ASSOCIATIONS OF THE PAOTE, SANMEN, AND MALAN DEPOSITS AND THEIR SIGNIFICANCE.

Writing on "Chinese climatic changes in Tertiary and Quaternary", Andersson says :—

> The first time that we find a tolerably preserved land-surface with indications as to the climate existing at that period is the transition between the Miocene and Pliocene. This is represented by red clays[1] containing well-preserved and rich remains of the so-called Hipparion fauna, a complex of predominantly steppe-forms known from a zone stretching across a good part of Eurasia, known particularly from Pikermi and Samos in Greece, Maragha in Persia, and a number of Chinese localities in Honan, Shansi, Shensi, and Kansu. This fauna, which includes the three-toed horse, numerous rhinoceros, giraffes, camels, antelopes and carnivores, indicates that at the period in question a steppe-like climate was ruling in China. That this climate was not universal is however shown by our discoveries in central Shansi, where the deposits are not of clay but sand, and such forest types as elephant, stag and pig appear. Even fish-remains occur, indicating lakes and rivers. The Ertemte fauna from Inner Mongolia includes beaver, waders, frogs and fishes indicating a Pliocene lake, probably bordered by forests of no small dimensions in the places where to-day the Mongolian steppe stands barren alike of trees and standing water.
>
> We thus find that during the Miocene-Pliocene transition the distribution of climatic conditions was so to speak the reverse of to-day. Mongolia was forested and water-fed, while North China (which might be well-forested had not man cut the trees down) was a steppe with sparsely distributed woods and water-courses.[2]

Andersson's first tabulation of the Kainozoic faunal association[3] has recently been brought up to date in Teilhard and Young's important advance report on the fossil remains from the Choukoutien (*Sinanthropus*) caves.[4] Teilhard here suggests that, whereas till now treated as Pontian in type, they may prove to be a composite group gathered from more than one horizon, containing Middle Pleistocene as well as true Pontian forms. Andersson's Ertemte Beds, for instance, lie unconformably over faulted red clays with Pontian fossils.

[1] i.e. of the Paote Stage.

[2] "Kinas klimatväxlingar i tertiär och kvartär tid," *Ymer*, vol. iii, 1925, Stockholm (translated by Dr. E. Nyström, revised by G. B. B.).

[3] "Essays on the Cenozoic," *Geol. Surv. China Mem.*, A 3, 1923, Table 2, p. 152.

[4] *Bull. Geol. Soc. China*, vol. viii, 1929, p. 173.

(*b*) The molluscan fauna from the Sanmen beds was diagnosed by Ohdner as indicating a warm climate. The mammalian remains found later bear out this conclusion. So far, it seems that the Sanmen group includes fauna of two horizons, which have much in common, but which are distinguished in each case by a few special types. The Nihowan subgroup seems to include slightly more primitive forms and is probably late Pliocene, while the Choukoutien fauna with Peking Man is basal Pleistocene. The general assemblage is Villefranchian and includes as most characteristic *Hyena sinensis*, *Elephas cf. namadicus*, *Rhinoceros cf. sinensis*, *Machairodus*, *Meles*, *Canis sinensis*, large horse and sheep, with special types of *Siphneus* and *Ochotona*. The older subgroup has *Cervus rusa*, *Cervus munjack*, primitive bison, *Chalicotherium* and a large *Hipparion*, while the early Pleistocene forms are *Cervus sika*, special *Euryceros*, *Bison*, and primitive *Bubalus*.[1]

(3) Whereas the Paote fauna had *western* affinities, and the Sanmen group show distinct *southern* influence, the true loess (Malan) fauna had a *northern* connection and indicates a cold climate. Teilhard and Young [2] have compiled a list of the more typical forms ; these include both *Elephas namadicus* and *E. primigenius*, *Rhinoceros tichorhinus*, *Cervus elaphus*, *Hyaena crocuta*, with typical *Euryceros* and *Bison* and modern rodents. These indicate a Middle Pleistocene date.

Two fossil forms of special interest are the ostrich egg *Struthiolithus* [3] and the only known example of plant remains, *Celtis barbouri* Chaney, a type of Pleistocene hackberry,[4] which fit in with the picture given above of climatic conditions during the loess epoch.

Age and Correlation of the Loess.

No satisfactory attempt has been so far made to establish any close connection between the deposition of the Chinese loess and geological events elsewhere. But it now seems worth while to suggest a tentative correlation, recognizing that such speculation may not have the same scientific basis as conclusions given in the earlier sections of this paper.

The conditions of loess accumulation are specialized enough to demand climatic influences of an abnormal kind, suggesting a more than regional control, likely to be of world-wide character.

A connection with some phase of the Pleistocene Ice-age at once suggests itself. No direct link has been established between the loess and the two valley-glaciations of the Altai recorded by Berkey and Morris,[1] nor with Dainelli's four glacial stages of the Karakoram,[2] nor with similar events in the Tibetan Alps.

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[1] Teilhard, loc. cit.

[2] Teilhard, loc. cit.

[3] Andersson, *Cenozoic of Northern China*, p. 53. Barbour, *Geology of the Kalgan Area*, p. 66.

[4] R. Chaney, " Hackberry Seeds from the Pleistocene Loess of Northern China," *Amer. Mus. Nat. Hist.*, Novitates No. 283, 1927.

But if the times of greatest ice-extension accompanied an accentuation of the winter pressure-distribution and a corresponding waning of the summer monsoon effect, the general conditions for loess development can be accounted for.

This would make the times of loess generation coincide with the glacial maxima, or at least with the periods of lowest mean temperature within the glacial cycles.[3] Two such periods are called for—corresponding to the loess deposits of the later Sanmen and of the Malan Stages. Each of these formations appears to be an indivisible unit and so far careful study reveals no other loessic horizons.

The Sanmen deposits yield fossils of Villefranchian type. Whatever views are held as to the identity and independence of the Günz Glaciation,[4] the Sanmenian cannot be younger than the Mindel Glacial Stage, so that the loessic deposits at the top of the formation can be correlated with the high-pressure peak of that glaciation.

On faunal grounds the Malan Stage might be either of Riss or of Würm age. If it is limited to either one, we may ask why no corresponding deposits have been anywhere found for the other. Since the accepted place for the Mousterian cultures has been in the Riss-Würm Interglacial Epoch, the discovery of quasi-Mousterian implements at the base of the Malan loess presented a dilemma with no obvious solution, unless :—

(1) The Riss glaciation had no loessic counterpart in this area—a hypothesis for which there is no ground—or

(2) The period of loess accumulation lasted through both Riss and Würm Glacial epochs, but for some reason was unevenly distributed, or locally scoured, so that the areas of the quasi-Mousterian *foyers* were free of Rissian loess—or

(3) The Loess represents both the Riss and Würm Epochs, but the cultures evolved in the East (or spread thither from an intermediate dispersal centre) before their appearance in Europe displaced the more primitive industries.

With regard to the last explanation, it should be noted that the fossil types present all belong to a single natural association. In fact, the work of Teilhard, Young, and others brings out clearly the fact that the Pleistocene of China shows only two groups—

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[1] *Geol. Soc. Amer. Fortieth Ann. Meeting*, Prelim. Abst., p. 5, Cleveland, 1927.

[2] *Studi sul Glaciale*, vol. i, Bologna, p. 600 ff.

[3] It is interesting to find the same connection between loess-development and glaciation put forward in an analysis of Ice-age conditions in Europe by Woldstedt recently reviewed in this Magazine. He divides the Loess "into four stages of formation, with three intermediate stages of weathering, and considers that these represent the whole of the compound glacial period in eastern Europe, Loess being formed during glaciations and denuded during the interglacials" (R. H. R., in *Geol. Mag.*, July, 1930, p. 335, reviewing P. Woldstedt, *Das Eiszeitalter*, Stuttgart, 1929).

[4] Cf. Josef Bayer, *Der Mensch im Eiszeitalter*, vol. i, Leipzig, 1927.

the *warm* Sanmen association followed by the *cold* Malan one. Recent studies of the European Pleistocene associations point to a similar sequence for the two main groups—warm followed by cold. There is increasing ground for the conviction that the Riss and Würm Glacial epochs were closely linked and represent essentially a double advance within a single relatively cold period.[1] On this interpretation, the Malan loess is the representative of this Riss-Würm twin-group.

With regard to the date of the Chinese Palaeolithic and the problem this raises in relation to the loess, recent revisions by Breuil and others place the Chellean well back in the Mindel-Riss Interglacial, so that a somewhat greater antiquity for the Mousterian in Europe is now generally conceded than was formerly granted. Hrdlicka goes so far as to say "The Mousterian or Neanderthal phase of man begins towards the end of the warm main interglacial". Even if it is allowed that its appearance there does not go back much beyond the close of the Riss, its origin farther to the east may well have been considerably earlier. For, as Boule has it, "Western Europe . . . . is only an advanced cape of Eurasia, a kind of cul-de-sac where the successive waves of many human tides come to break and die out."[2] Even if the dispersal centre in this case lay in some intermediate region so that the culture did not reach China at once, it still may well have done so long before it came to Europe. In addition it thus would have only an indirect relationship with the classic Mousterian through their common mid-Asiatic ancestor, a fact explaining its somewhat anomalous character.

The Malan Stage was preceded and followed by the periods of greater precipitation of the Chingshui and Panchiao Stages. The latter corresponds to the post-Würm transition to present-day conditions, the former apparently to the Mindel-Riss Interglacial. It thus seems that the pluvial periods do not correspond to glacial stages, nor are the arid days of the loess the counterpart of the warmer interglacial epochs. Instead, the prime control of both loess and glaciation seems to have been the slight but world-wide fall in temperature.

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[1] Cf. among others, A. Hrdlicka, "Neanderthal Phase of Man" (Huxley Memorial Lecture), reprinted in *Smithsonian Ann. Rep.*, 1928, Washington, 1929, p. 618.

[2] Quoted by D. A. E. Garrod, "Nova et vetera," *Proc. Prehist. Soc. East Anglia*, vol. v, 1927, p. 261.

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A New *Ceratotrochus* from the Upper Cretaceous of Portuguese East Africa.

By J. W. Gregory, LL.D., D.Sc., F.R.S.

THREE small simple corals were collected by Mr. F. P. Mennell from the Upper Cretaceous of the Cheringoma district, Portuguese East Africa. The area is of special geological interest as it includes the southern end of the Great Rift Valley and furnishes useful evidence as to the date of the formation of that valley. A coral from almost the same horizon has been figured by Schlosser, and, as it is clearly a different species, the horizon may be expected to yield a good fauna of simple corals.

Ceratotrochus Milne Edwards and Haime, 1848.

Ann. Sci. Nat. **3**, ix, p. 248; *Hist. Nat. Cor.* ii, 1857, p. 73; type sp. *Turbinolia multispinosa* Michelotti, 1838; *Spec. Zooph. dil.*, p. 71, pl. ii, f. 119; and Michelin, 1841, *Icon. Zooph.*, p. 42, pl. ix, f. 5. Miocene. Tortona.

Ceratotrochus mennelli n. sp.

Diagnosis.—Corallum with a pointed base; much compressed laterally, with flattened sides. Costae thick, numerous, subequal; about 12 in 5 mm. Septa about 60 in transverse section at a little above half the height of the corallum. The primary and secondary septa are clavate, being thickened towards the centre, but they end in a pointed inner edge. Columella of many small vertical rods. Epitheca none.

Dimensions.—Corallum: height, 18 mm.; diameter, 17 × 11 mm.

Distribution.—Upper Cretaceous, between the Bawa and Chiti Rivers on the western side of the Inyaminga anticline, Cheringoma district, Portuguese East Africa.

Figure.—The type specimen from the side and in cross section, × 2 dia.

Affinities.—This species is represented by three specimens sent by Mr. Mennell. The internal structure is not well preserved and left some doubt as to the genus. The thickened inner ends of the septa suggested that the coral might have a lamellar columella; but a transverse section shows that the columella is fasciculate and that there are no pali. Hence the genus is *Ceratotrochus*.

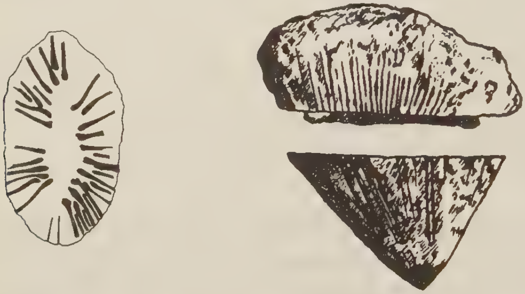

Fig. 1.—*Ceratotrochus mennelli*, n.sp., from Portuguese East Africa.

The nearest species is *C. exiguus* From., from the Turonian of the Var in Southern France. That species is more laterally compressed, but is only a third of the size and has not the club-shaped septa. This coral may also be compared with an imperfect specimen from the glauconitic sands of the Upper Cretaceous at Inhoca, which has been described and figured by M. Schlosser[1]; but that specimen has eight or so of the costae much thicker than the rest; also the corallum is more laterally compressed, the axes of the cross-section being 13 and 5 mm.

Among Upper Cretaceous species is *Ceratotrochus polonicus* Siemiradzki,[2] from the Maastrichtian of Lvow (Lemberg), of which the single specimen was twice as large, is circular in section and has a large calicular cavity. *C. mennelli* is more similar to *C. kefersteini*

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[1] "Uber Tertiär and obere Kreide aus Portugiesisch-Ostafrika," *Abh. Bayer. Akad. Wiss.*, Math-nat. Kl., xxxii, pt. 2, 1928, p. 18, pl. ii, f. 6.

[2] J. Siemiradzki, "Korale gornokredowe Polski," *Kosmos*, Lvow, vol. li, 1927, p. 324, fig. 5.

Krejci,[1] from the Miocene of Oerdekenbrück, North Germany; the two species agree in general form and the conspicuous first two cycles of septa; but these septa in the German species are not clavate and the axial cavity is larger.

Mr. Mennell states that the Nummulitic Limestone begins about 40–50 feet higher up in the sequence than the bed which yields the simple corals.

REVIEWS.

The Titanotheres of Ancient Wyoming, Dakota, and Nebraska. By Henry Fairfield Osborn. *U.S. Geological Survey Monograph* 55. Two volumes, quarto. xxiv + xi + 953 pp., with 236 plates and 797 text-figures. Washington: U.S. Government Printing Office, 1929.

THIS is probably the completest and most elaborate monograph on a group of fossil animals which has ever been published. The subject is dealt with from every possible aspect, both geological and zoological. There are very complete bibliographies provided, and no expense has been spared on the illustrations. The author is to be warmly congratulated on the completion of a work, the preparation and writing of which extended over half a normal lifetime. The monograph took origin in the researches of Marsh, whose first contribution to the study of the Brontotheriidae was issued in 1874, and from that date onwards until 1891 this pioneer worker continued to publish memoirs which formed the original basis of the present monograph. Since 1900 Professor W. K. Gregory has co-operated with Professor Osborn in his studies, and the chapter on the musculature, besides certain other sections of the work, are written by Professor Gregory.

The elaboration of such an extensive monograph on a single group of animals will probably be thought by some to require justification. This is to be found in the fact that the Titanotheres form the most complete series of fossils illustrating the phylogeny of any group of mammals so far discovered excepting the horses. Moreover, the Titanotheres were much more highly differentiated than the horses. In the former group we see illustrated to a degree that is unique among mammals the evolution of a great and vigorous stock, the members of which, while retaining fundamental hereditary resemblances, show marked divergences in characters and habits that developed continuously in response to changed conditions of life.

Of the geological principles enunciated in this work the most outstanding is that of the division and correlation of the stratigraphical formations in the Eocene and early Oligocene periods by mammalian life zones and by the subdivision of these zones.

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[1] K. Krejci, "Norddeutsche Miocänkorallen," *Jahrb. Preuss. Geol. Landes.*, xlvi, 1926, p. 462, pl. vii, f. 8, 14.

Sixteen zones are now recognized, each of them characterized by a varied mammalian fauna and by the sudden appearance or disappearance of various vertebrate groups. Many of these zones are related to changes in climate or general environmental conditions such as afforestation. Moreover, sedimentary deposits in different geographical basins or areas are correlated in such a manner as to present the complete life story of the Eocene period. The author predicts that the sixteen life zones now recognized will be increased to twenty or more as a result of future discovery.

The progressive history of Titanothere evolution as described in great detail by the author is one of arresting interest. The earliest species of the group, which were subcursorial in the anatomy of their limbs, are shown to have developed in a country partly open and partly forested, frequenting meadows, river valleys, and plains that were flooded at certain times of the year. At least one genus became aquatic, or at any rate amphibious, and others were almost certainly semi-aquatic. Then, at the beginning of the Oligocene period the Titanotheres entered the region of the savanna-like "Great Plains", a country partly open and partly forested, with great winding rivers. And here, after diverging in different directions, each line at its period of greatest apparent prosperity, as manifested by its having attained its maximal size (with only one known exception), some time about the middle of the Oligocene, suddenly became extinct. Concerning the causes of extinction the author makes it clear that inadequate cranial capacity could have played no part, since the brain steadily increased in size in passing from the Eocene to the Oligocene forms. Neither is there any sign of a numerical increase such as has been found with other groups as they approached extinction. On the other hand, evidence is brought forward that the influence of the teeth was probably an important factor in extinction. The Titanotheres seemed to have reached a cul-de-sac of evolution in their molar teeth which failed to meet the new conditions of food on the Great Plains, but it was the mechanical pattern of the teeth rather than the size which was unadapted to the new environment. The author points out in this connection that every family of mammals that experimented with its teeth of this particular type (Anoplotheriidae, Anthracotheriidae, Chalicotheriidae) became extinct sooner or later in Tertiary times, and that the only type with buno-selenodont molars which survived through the Miocene period was the Chalicothere, and probably because it was a forest-frequenting animal. Subsidiary causes, other than inadequate dentition, may have contributed to the extinction of the Titanotheres, and we may note, as illustrating the thoroughness with which the author treats of his subject, that he discusses at length the effects of rinderpest and other epidemic diseases as probable causes of elimination in various groups of mammals.

In a short notice such as the present it is impossible to do more than indicate the scope of this important monograph. After an introductory chapter in which are set out the main geological and anatomical principles that are followed, we pass to an account of the different environments of the Titanotheres and the effect of adaptive radiation on their variation. The third chapter describes the discovery of the Titanotheres and the original accounts of the types, and this is followed by a systematic classification. The latter is based on the characters of the skull and teeth, as set forth in chapters v and vi, combined with those of the limbs and feet as dealt with in chapter vii. In the next chapter by Professor Gregory an attempt is made at the restoration of certain Titanothere types, this being based on the study of the muscular anatomy as deduced from the skeleton. Chapter ix deals with the mechanics of locomotion in the evolution of limb structure as bearing on the form and habits of the Titanotheres and the related Perissodactyla. Lastly, there are chapters on the origin and evolution of the Titanotheres and other ungulates, and the probable factors in the process.

The final conclusions reached are necessarily to some extent speculative, but certain of the results are of outstanding importance, and no student of organic evolution can afford to ignore them. In discussing the question of continuity or discontinuity in descent, Professor Osborn shows that in the evolution of the manus in the ascending series of Titanotheres there is a perfect transition from the cursorial through the mediportal to the graviportal type, modified throughout by certain peculiar Titanothere family tendencies, that the same is true for the Titanothere pes, or to take the cases of single bones, that the os magnum of the carpus and the astragalus of the tarsus display similarly a complete succession of comparable intermediate stages. The author contrasts these facts with the statement by Punnett that transitional forms are uncommon, and, following Scott and Matthew, criticizes the examples of discontinuity cited by Bateson. "The fact is," he says, "that intermediates are found abundantly in mammalian zoology as well as in palaeontology." Professor Osborn believes also that the balance of evidence in Titanothere evolution is against the Lamarckian principle of the inheritance of acquired characters. In this conclusion he differs from Cope, who failed to see that the theory does not adequately account for many of the adaptations of proportion. The possibility, however, of the operation of the principle cannot be said to be entirely ruled out. Professor Osborn is of opinion, further, that the evidence is strongly against the Darwinian hypothesis of the selection of minute variations as being of survival value, but on the other hand, that the principle affords an explanation of the evolution of those larger proportions, such as the limbs of the unborn colt and the general acceleration of adult limb dimensions into foetal stages which are of utility in protecting the young at birth.

The author's chief constructive contribution to the philosophy of evolution is his formulation and working out of the tetrakinetic principle, and as this idea dominates much of the work it will be well to summarize it in his own words. "In each Titanothere the phenomena of life represent the action, reaction, and interaction of four complexes of physico-chemical energy; those of (1) the geographic environment; (2) the developing organism (protoplasm, germ chromatin of the body cells); (3) the germ chromatin of the reproductive cells, seat of heredity; (4) the life environment. Upon the resultant actions, reactions, and interactions of latent potential (stored) and kinetic (active) energy in each organism natural selection is constantly operating wherever there is competition with the corresponding actions, reactions, and interactions of other Titanotheres and other organisms. According to this energy conception of evolution, Darwin's principle of natural selection is not set aside, but remains extremely important; it is constantly operating not only between organisms as a whole, but on their separate parts, and especially upon their separate manifestations of energy, that have or lack survival value."

This theory will undoubtedly evoke criticism, but it is impossible to withhold admiration for the painstaking way in which the author has applied it in his interpretation of Titanothere descent.

F. H. A. M.

The Copper Deposits of Michigan. By B. S. Butler, W. S. Burbank, and others. U.S. Geol. Survey, *Professional Paper* 144. 1929.

The Ores of the Northern Rhodesia Copper Belt. By A. M. Bateman. *Econ. Geol.*, xxv, 365. 1930.

THE subjects discussed in both these publications are too large and too complicated for adequate review in any journal not specially devoted to economic geology. They are only referred to here in order to point out their existence and to emphasize the fact that in both cases the authors have come to the conclusion that these, probably the greatest copper deposits of the world, are of magmatic origin. Professor Bateman thinks that the Rhodesian copper disseminations, as well as the great copper-radium deposits of Katanga, are due to intrusion of granites into sediments susceptible to selective replacement, much of the predominant chalcocite being primary or, as he prefers to call it, hypogene, while the authors of the other splendid monograph refer the introduction of the copper in the Keweenawan rocks to the intrusion of the enormous mass of the Duluth gabbro. This bears out a generalization put forward some years ago by the present reviewer that the element copper is characteristic of magmas of a very wide range of acidity, in contradistinction to certain other metallic elements, which belong definitely to either the acid or the basic end of the differentiation series, such as tin, tungsten and molybdenum at the acid end, and chromium and platinum in the ultrabasic fractions.

R. H. R.